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EXPERIMENTAL

ELECTRICAL ENGINEERING

AND

MANUAL FOR ELECTRICAL TESTING

FOR ENGINEERS AND FOR STUDENTS IN
ENGINEERING LABORATORIES

BY

V. KARAPETOFF

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CHAPTER XXI.

ELECTROSTATIC CAPACITY.

426. Physical Conception of Electrostatic Capacity. — Let two metallic plates C (Fig. 329) be brought into proximity to each other but separated by an air space or by some other insulation. This combination of two plates with a dielectric intervening is called an *electric condenser*. When the plates are connected to a source of continuous voltage a transient current flows through the circuit, and the plates are said to be charged with equal and opposite quantities of electricity. Or, according to a more modern view, equal and opposite quantities of electricity are displaced through the dielectric, subjecting it to an electrostatic stress. The quantity of electricity displaced per unit e.m.f. between the plates of a condenser is called its *electrostatic capacity*. The unit of capacity in the ampere-volt-ohm system is called the "farad." A condenser is said to have a capacity of one

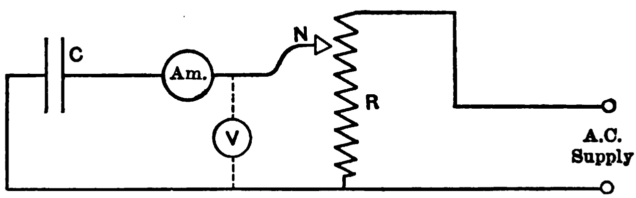


FIG. 329. A convenient method for varying the voltage at the terminals of a condenser.

farad, if one coulomb of electricity is displaced through the circuit, at a pressure of one volt between the plates. The coulomb is the quantity of electricity supplied by a current of one ampere during one second.

The farad may also be defined by the volt and the ampere without introducing the conception of the coulomb. *A condenser has the capacity of one farad if it takes a charging current of* 1 *ampere when the voltage at its terminals varies at a rate of* 1 *volt per second.* The farad is too large a unit for practical purposes; therefore capacity of condensers is usually measured in millionth parts of a farad, or in *microfarads*.

The presence of capacity in an alternating-current circuit modifies the current and the voltage relations. When, for instance, a con-

denser is connected in parallel with the load, the alternator has to supply not only the load current but also an additional current for periodically charging and discharging the condenser.

The following analogy may make clearer the action of a condenser. Imagine a water-supply pipe with a branch opening to which an elastic bag is connected, the bag and the pipe being filled with water. As long as the pressure remains constant, the presence of the bag does not interfere with the regular flow of water through the pipe. But should the pressure in the pipe increase, part of the water, instead of flowing through the pipe, enters the bag and stretches it, until its elasticity balances the increased pressure. Should the pressure in the pipe decrease, the elasticity of the bag forces part of the water back into the pipe. Thus, if the pressure in the pipe varies periodically, there is a periodic flow of water in and out of the bag, and the conditions of flow become more complicated than if the pipe were solid.

In a similar way, the flow of current in alternating circuits is modified by electrostatic capacity. When the voltage increases, extra current flows through the line to charge the condenser; when the voltage is on the decrease, the condenser is partly discharged through the line. In long cables and overhead transmission lines, capacity is not concentrated in one place, but is distributed along the line. Each element of the line acts as one plate of a small condenser, the earth, or another wire of the same line acting as the other plate. To extend the above analogy to this case, the pipe itself must be imagined as made of an elastic material, so that its cross-section varies with the applied pressure.

427. Electrostatic Capacity in Practice. —The most important practical cases in which capacity is brought into play are:

(1) In submarine telegraph cables, where capacity is so large that an appreciable time elapses before any current reaches the further end of the cable. The first few moments after the circuit is closed, all the current is used for charging the cable itself, so as to bring it up to the required potential. This circumstance limits the speed of transmission of signals.

(2) In high-tension cables and very long overhead transmission lines, capacity has quite a noticeable disturbing effect on the transmission of power, causing at times an abnormal rise of potential.

(3) Electrostatic capacity in telephone lines considerably affects the quality of speech. To minimize this effect, telephone cables are constructed so as to have as little capacity as possible. Inductance coils are sometimes inserted in long telephone lines to neutralize the effect of capacity.

(4) Condensers are useful in cases where direct current should not flow through a certain part of the circuit, while alternating currents should pass through it with as little opposition as possible. Condensers are used for this purpose in central-energy telephones (see Figs. 324 and 326, Vol. I).

(5) Condensers are an indispensable part of wireless telegraph outfits; also in other cases where it is necessary to produce electric oscillations.

(6) Condensers are useful in many electrical investigations as auxiliary means for measuring various quantities, eliminating or accentuating higher harmonics, etc.

428. Factors Affecting the Capacity of a Condenser. — The electrostatic capacity of a condenser depends entirely upon the form, the arrangement, the dimensions of the metallic plates, upon their distance from one another, and upon the nature of the dielectric between the plates. Capacity is increased with the increased surface of the plates *C* (Fig. 329); in other words, more electricity is displaced with the same voltage between the plates. The reason is that with larger plates a larger layer of dielectric is subjected to an electrostatic stress, which is the cause of the displacement. Bringing the plates closer together also increases the capacity, because a thinner layer of dielectric is subjected to the same voltage. The consequence is that the stresses and the displacement of electricity in it become larger.

Capacity is also increased by substituting various insulating materials for air. In other words, such materials are more *yielding* to the electric stress, the same stress producing in them a larger displacement of electricity, than in air.

Thus, substituting paraffine for air increases the capacity of a condenser about twice; the use of hard rubber increases it 2.5 times, etc. The number of times by which capacity is increased by the substitution of some other insulating material for air is called the specific inductive capacity of the insulating material. It is about 2.5 for rubber, about 2 for paraffine, and varies between 2 and 3 for many other substances.

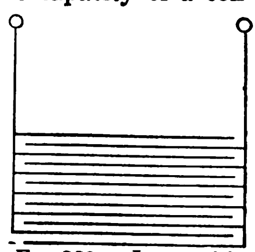


FIG. 330. Interposition of metal sheets in a condenser, to increase its capacity.

429. Construction of Condensers. — The capacity of condensers used in practical work is too large to be obtained by two plates, unless the plates be given enormous dimensions. It therefore becomes necessary to use several plates (Fig. 330) connected alternately to opposite terminals. An air-insulated condenser of this kind is shown in Fig. 331; it is used as a standard for measuring small capacities. For

larger capacities, plates must be brought much closer together, and their number greatly increased. Besides, it becomes necessary to use a dielectric other than air, since the thin metal sheets are not strong

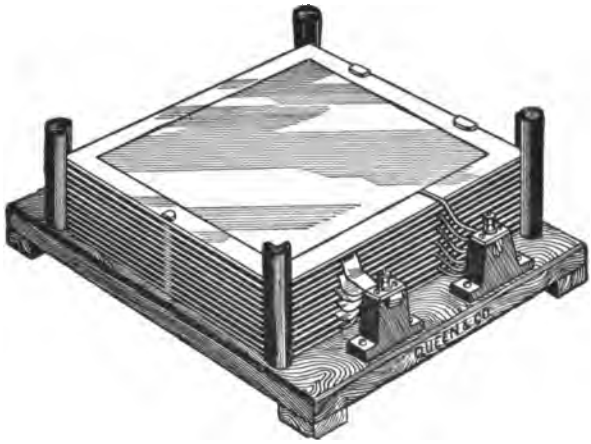


FIG. 331. A standard air condenser.

enough to support themselves. This also increases the capacity of the condenser from two to three times, because of the higher specific inductive capacity of dielectrics other than air.

Mica is used for insulation in standard condensers; also in those intended for high voltages. Such condensers consist of sheets of tinfoil with sheets of mica between them. The whole is firmly pressed together

FIG. 332. An adjustable mica condenser.

in order that the distance between the plates and consequently the capacity shall remain unaltered. A more satisfactory method than using tinfoil is to have each sheet of mica coated chemically with a thin film of silver. A standard mica-condenser is shown in Fig. 332; it

is subdivided into sections of 0.05, 0.05, 0.2, 0.2 and 0.5 microfarad. By simple combinations of plugs, several values of capacity may be obtained between 0.05 and 1 microfarad (Fig. 333).

Mica condensers are quite expensive; therefore, where high accuracy and particularly high insulation are not required, sheets of tinfoil are

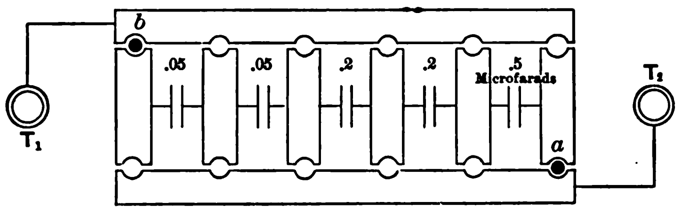


FIG. 333. Arrangement of sections in the condenser shown in Fig. 332.

insulated with paper instead of mica. Each sheet of paper is dipped in hot paraffine during the construction, and the whole is immersed in paraffine after completion, in order to exclude air. This makes the condenser a solid mass, and insures constant distances between the sheets of tinfoil. A paper condenser for voltages up to 500 volts, ad-

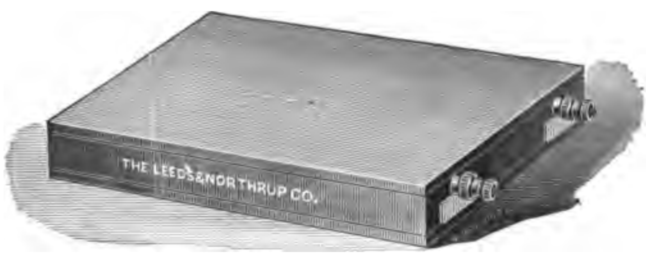


FIG. 334. A simple paper condenser.

justed within 3 per cent, is shown in Fig. 334. Paper condensers may also be subdivided into sections, as in Fig. 332.

430. Condensers in Series and in Parallel. — Condensers may be connected in series and in parallel, like resistances, and it is necessary to know how to calculate their combined capacity.

(*a*) *Condensers in parallel.* Suppose several condensers (Fig. 335) of capacities c_1, c_2, c_3, etc., to be connected in parallel across a line having a pressure E. The problem is to find the capacity C of an equivalent condenser, such that can displace at the same pressure E the same quantity of electricity as the given condensers together.

Let the quantities stored be $q_1, q_2, q_3. \ldots$ According to the definition of capacity (§ 426), we have

$$q_1 = c_1 E; \ q_2 = c_2 E; \text{ etc.}$$

For the equivalent condenser

$$q_1 + q_2 + \ldots . = CE.$$

Substituting we find

$$C = \sum c;$$

in other words, the combined capacity of condensers in parallel is equal

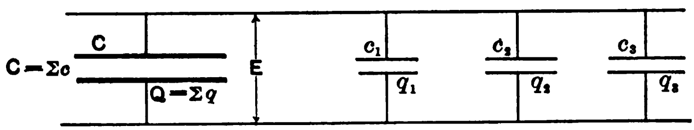


FIG. 335. Addition of capacities in parallel.

to the sum of their capacities. This result could be foreseen from the physical conception of capacity as the *permittance* of a dielectric.

(*b*) *Condensers in series.* Condensers connected in series are shown in Fig. 336. The electric charge q in each of them is the same,

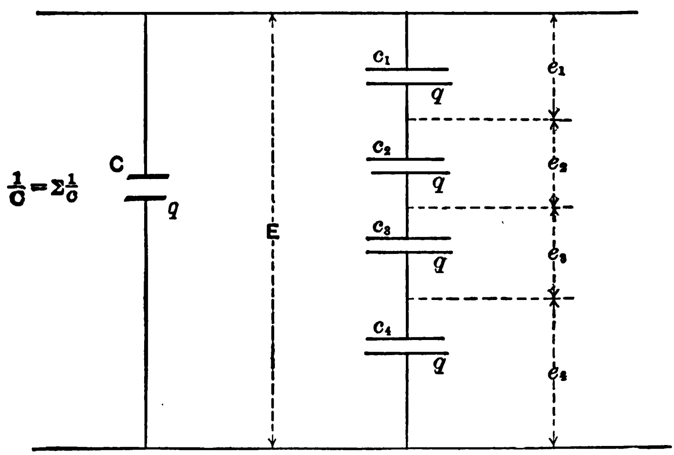


FIG. 336. Addition of capacities in series.

though they may have different capacities. This is because all the condensers together offer but one path for the displacement of a certain quantity of electricity q between the line terminals. Since electricity behaves like an incompressible fluid, q is the same throughout

the circuit. The problem is to find the capacity C of *one* condenser (Fig. 336) such that would allow of the same displacement q at the same line voltage E. Let the voltages across the given condensers be $e_1, e_2, e_3, \ldots$; we have then

$$q = c_1 e_1 = c_2 e_2 = c_3 e_3 = \ldots .$$

For the equivalent condenser

$$q = CE = C\,(e_1 + e_2 + e_3 + \ldots);$$

Substituting the values of e_1, e_2, e_3, etc., we find

$$q = C\left(\frac{q}{c_1} + \frac{q}{c_2} + \frac{q}{c_3} + \ldots\right),$$

or

$$\frac{1}{C} = \sum \frac{1}{c}.$$

This can be expressed in words by saying, that the sum of the reciprocal values of capacities connected in series is equal to the reciprocal value of the equivalent capacity. This is analogous to the expression for ohmic resistances in parallel (see § 8).

Let us apply these results to the standard condenser shown in Figs. 332 and 333. The largest capacity is obtained by connecting all the sections of the condenser in parallel, with plugs inserted alternately in the two rows of holes, as in Fig. 332. The smallest value of capacity corresponds to all the sections in series, with plugs at a and b (Fig. 333). Intermediate values are obtained by other suitable combinations of plugs. For instance, to get 0.15 microfarad, two sections of 0.2 mf. each, are connected in series, which gives 0.1 mf.; then 0.05 mf. is connected in parallel with them. With all the sections in series, we have

$$\frac{1}{C} = \frac{2}{0.05} + \frac{2}{0.2} + \frac{1}{0.5} = 52,$$

or $C = 1/52$ mf.; this is the smallest value obtainable with this condenser. The largest capacity with all the sections in parallel is

$$2 \times 0.05 + 2 \times 0.2 + 0.5 = 1 \text{ mf.}$$

431. Methods for Comparing Capacities. — Most practical methods for measuring capacity are based on comparing the capacity under test to that of a standard condenser. The calibration of standard condensers themselves is done by special methods, and is outside the scope

of practical engineering. The following are the methods of comparison commonly used:

(1) Direct-discharge method;
(2) Method of mixture;
(3) Thomson zero method.

In addition to these, capacity may be measured in terms of volts and amperes with sinusoidal alternating currents. All these methods are described below.

432. Direct-Discharge Method. — A standard condenser of capacity C_1 is connected across a battery and charged at a certain voltage. Then it is discharged through a ballistic galvanometer (§ 119); let the deflection be d_1. The same is repeated with the condenser under test,

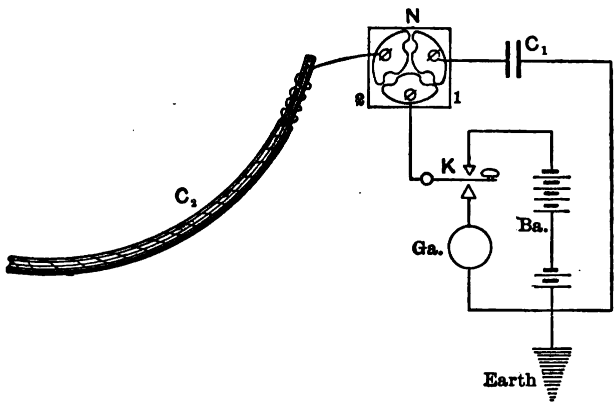


FIG. 337. Direct-discharge method for comparing capacities.

the unknown capacity of which, C_2, is to be determined; let the deflection be d_2. Then, if the charging voltage is the same in both cases:

$$C_1 \div C_2 = d_1 \div d_2.$$

This is true since electric charges on two condensers, at the same voltage, are proportional to their capacities (§ 430 a). On the other hand, deflections of a ballistic galvanometer are proportional to discharges through it; consequently, in the case under consideration, galvanometer deflections are proportional to the capacities of the condensers.

When the capacity of a long cable laid underground is measured by this method, the connections are as shown in Fig. 132. The lead sheathing of the cable serves as one plate of the condenser; as it is con-

nected to the ground, one pole of the battery must also be grounded to complete the circuit. N is a commutator; inserting a plug into the hole 1 connects the standard condenser C_1 to the battery. The key K is normally pressed against the upper contact, so that C_1 is charged. Pressing the key discharges C_1 through the galvanometer. Then the plug is inserted into the hole 2, when the cable is connected in place of C_1, and the same test repeated. The ratio of the deflections gives the ratio of the capacities.

433. Method of Mixtures. — This method is illustrated in Fig. 338 and used for measuring small capacities, such as the capacity of tele-

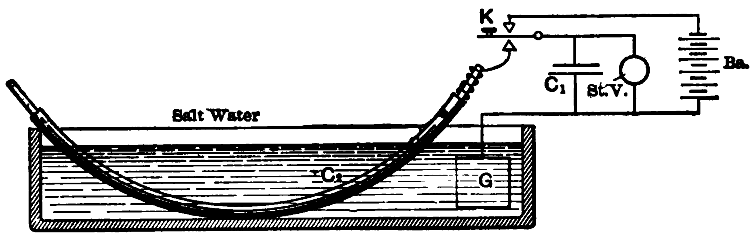


FIG. 338. The method of mixtures, for comparing capacities.

phone cables, or of short pieces of power cables. It consists in adding the unknown capacity C_2 to a standard condenser C_1 which has been previously charged; C_2 is then calculated from the resulting drop in

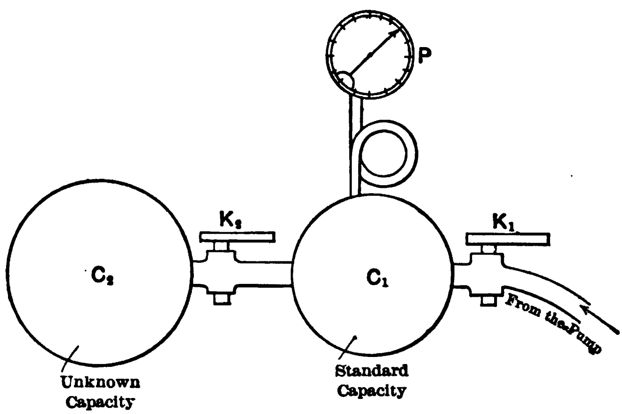


FIG. 339. Mechanical analogy illustrating the method of mixtures.

voltage of C_1. A mechanical analogy, shown in Fig. 339, may help to understand the method. C_1 is a vessel of a known cubical (volume) capacity; C_2 is another vessel the capacity of which is to be determined.

Close the valve K_2 and connect C_1 by means of the valve K_1 to a source of compressed air. A certain pressure will be indicated on the gauge P. Now close K_1 and connect C_1 with C_2. The air expands into C_2 and the pressure is reduced. The resultant pressure depends on the capacity of C_2, which thus may be calculated from the pressure-volume law of gases.

In a similar way, the standard condenser C_1 (Fig. 338) is charged from the battery, and the voltage measured on the multicellular static voltmeter "St. V." (see Fig. 47); let the indication be E volts. The key K is then pressed, so that the charge is distributed between C_1 and C_2 connected in parallel; let the voltmeter indication drop to e. As the total charge is the same in both cases, we have

$$\text{charge} = EC_1 = e(C_1 + C_2),$$

from which C_2 can be calculated.

The capacity of the voltmeter itself can usually be neglected. If such is not the case, the above formula becomes

$$E(C_1 + c) = e(C_1 + c + C_2)$$

where c is the capacity of the static voltmeter. The capacity c may be determined by performing the above measurement with a condenser C_2 of a known capacity.

When testing telephone cables by this method, the specification usually requires that the test be made under the most unfavorable conditions (maximum capacity). These are obtained when the lead sheathing and all the conductors of the cable, but the one under test, are grounded.

434. Thomson Zero Method for Comparing Capacities. — This method, illustrated in Fig. 340, depends upon the two following operations: (1) The ratio of capacities is made equal to a ratio of resistances, which ratio can be determined with great accuracy; (2) Balance is obtained when the galvanometer returns to zero; this adds to the accuracy of the method, and makes it unnecessary to have a calibrated galvanometer.

Let the condensers C_1 and C_2 be connected as in Fig. 340; the key K_o is closed first, and a steady current established through the resistances R_1 and R_2. The keys K_1 and K_2 normally touch the upper contacts, so that the condensers C_1 and C_2 become charged. The voltage at the terminals of each condenser — and consequently the magnitude of the charge — depends upon the position of the slider N.

Now K_1 and K_2 are pressed down simultaneously. This allows the

positive charge of C_1 to neutralize all or a part of the negative charge of C_2; the other charges, no longer bound, neutralize each other to the same extent. The remaining charges are equalized through the galvanometer *Ga.*, by pressing the key K_3. The adjustment consists in finding such a position of the slider N that both condensers are charged with the same quantities of electricity. When such is the case, pressing the keys K_1 and K_2 completely discharges the condensers, so that the galvanometer does not deflect, when the key K_3 is closed.

When the correct position of the slider N is found, — with the

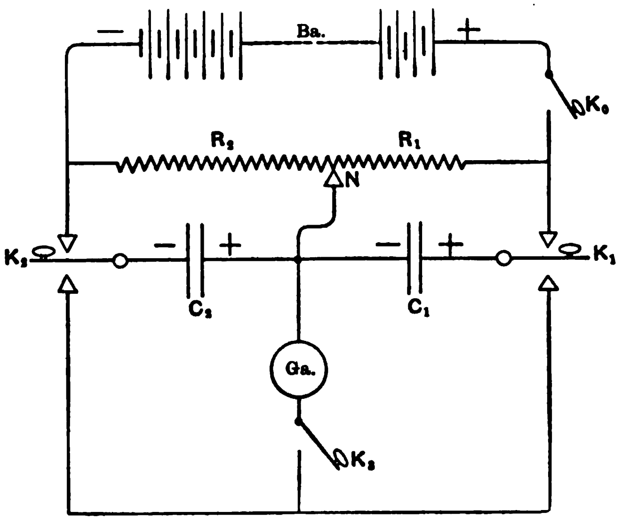


FIG. 340. The Thomson zero method for comparing capacities.

voltages across R_1 and R_2 equal to e_1 and e_2, — the following relations exist:

$$\text{charge} = e_1 C_1 = e_2 C_2.$$

But $e_1 : e_2 = R_1 : R_2$; eliminating e_1 and e_2 we obtain

$$C_1 R_1 = C_2 R_2.$$

From this formula the unknown capacity C_2 is calculated.

It must be remembered that some cables take quite an appreciable time, sometimes several minutes, to become fully charged. In the same way sufficient time should be allowed for the charges to equalize before closing the key K_3. When this method is used for determining the capacity of a cable whose sheathing is grounded, the necessary connections must be established through the ground. This is done by grounding the connection between the galvanometer and the slider N;

the sheathing of the cable acts as the positive terminal of the condenser C_2. The rest of the connections are the same.

In addition to the above three methods for comparing capacities, there are some others, mostly based on the use of a Wheatstone bridge. These methods, while seldom used in engineering, are well adapted for accurate scientific measurements. For a description, the reader is referred to standard works on physics.

435. EXPERIMENT 21-A. — Comparing Capacities of Two Condensers. — The methods are described in the three preceding articles. Try such of them as the apparatus at hand and the nature of the capacity to be measured allow. In each case take several readings, modifying the conditions (voltages, resistances and capacities) in such a way as to have a thorough check on the result. Ascertain the limits of accuracy of each method, and determine the conditions necessary for obtaining maximum accuracy. Connect condensers, or sections of a condenser, in series and in parallel, and check the relations derived in § 430.

436. Capacity in A. C. Circuits. — Consider a condenser C connected, as in Fig. 329, to a source of A. C. supply. As the main current flows through the rheostat R, by moving the slider N, any desired voltage may be had at the terminals of the condenser (potentiometer principle). This voltage is measured by the voltmeter V, — the current through the condenser is indicated on the ammeter Am. It may at first seem that no current can flow through the condenser, the circuit at the gap being open between the plates. A little consideration will show, however, that a condenser will become periodically charged with opposite quantities of electricity when an alternating voltage is applied at its terminals. This alternate flow of charging current back and forth, at the frequency of the supply, produces the same effect on the ammeter, as if the circuit were actually closed through a resistance.

We now desire to determine the value of the charging current which will flow through a condenser of a given capacity C, with a given alternating voltage E at its terminals, the frequency of the supply being n cycles per second. According to the definition of capacity given in § 426, a condenser takes in a charging current of 1 ampere, when the pressure rises at a rate of one volt per second, provided the capacity of the condenser is 1 farad. Therefore, with a capacity of C farads and the voltage rising at the rate of $de \div dt$, the charging current is

$$i = C\frac{de}{dt}.$$

Let the applied voltage vary according to the sine law, so that

$$e = E \operatorname{Sin} 2\pi nt.$$

Substituting this value of e in the above, we find

$$i = 2\pi nC \,.\, E \operatorname{Cos} 2\pi nt \quad \ldots \ldots \quad (1)$$

This equation shows that the charging current also varies according to the sine law. The wave of the current leads that of the voltage by 90 degrees; when the voltage is passing through its zero value, the current has already reached its maximum. These relations may be expressed by the equation

$$i_{eff} = 2\pi nC \,.\, E_{eff} \; (90°),$$

where (90°) denotes symbolically the phase relation between the current and the voltage. In this formula the capacity is expressed in farads; in practice, capacity is always expressed in microfarads. One microfarad is equal to 10^{-6} farads, so that

$$i_{eff} = 2\pi n\, C \,.\, 10^{-6}.\, E_{eff} \; (90°) \quad \ldots \ldots \quad (2)$$

From this formula the charging current through a condenser of a given capacity may be calculated for a given voltage and frequency. Conversely, by measuring the current and the voltage, capacity C may be calculated. This method of determining capacity is strictly accurate with sinusoidal voltages only; the presence of higher harmonics may appreciably affect the value of the current. This follows from the fact that each harmonic gives a charging current of its own, and the values of charging current increase in proportion to the frequency. Thus, in the case that the seventh harmonic of the e.m.f. wave amounts to only 5 per cent of the fundamental wave, the charging current due to the seventh harmonic will be $0.05 \times 7 = 0.35$, or 35 per cent, of the current due to the fundamental wave. This circumstance should be kept in mind when using alternating currents for measuring capacity.

437. EXPERIMENT 21-B. — Condensers in A. C. Circuits. — The purpose of the experiment is to illustrate the relations derived in the preceding article. Connect a condenser C, as in Fig. 329, using a resistance R and the slider N for varying the voltage at the condenser terminals. Take curves showing variations of the charging current with:

(a) Capacity of the condenser;
(b) Applied voltage;
(c) Frequency of the supply.

Connect a wattmeter so as to measure the power taken by the condenser; show that the charging current is practically wattless. A

small amount of power may be consumed in the condenser, due to imperfect insulation, and to what is called "dielectric hysteresis" in the insulation. If possible, vary the wave-form of the current (see § 646) and observe its effect on the charging current.

Report. Plot curves showing the effect of the factors (a), (b) and (c) on the charging current. Check a few points on these curves by the formula (2). Describe the test showing that the charging current is practically wattless. Give the effect of the wave-form on charging current.

438. Capacity Reactance. — Equation (2) shows that with alternating currents the expression $2\pi nC$, and not the capacity C alone, determines the charging current of a condenser. This is similar to the effect of reactance $2\pi nL$ (§ 98) which was there denoted by x. We shall denote accordingly

$$10^6 \div 2\pi nC = y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

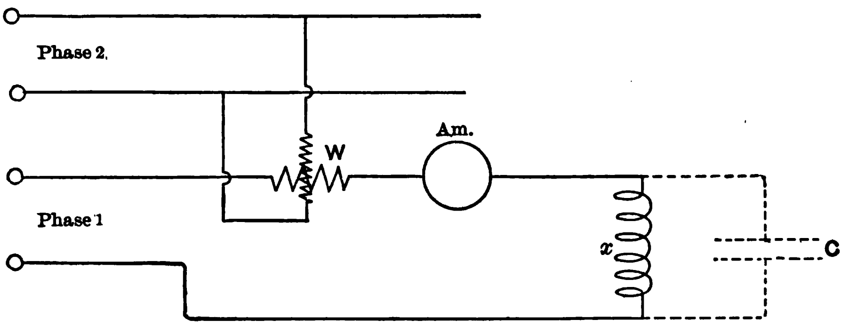


FIG. 341. An experimental proof that capacity acts as a negative inductance (measuring wattless power).

and call y the "capacity reactance" of a condenser, as distinguished from the magnetic reactance x. The capacity reactance is also expressed in ohms.

The considerations of §§ 103 to 112 may be applied to the case of capacity reactance, by substituting $-y$ for x. The sign minus is necessary, because current is lagging with magnetic reactance and is leading in the case of capacity. In this respect, capacity acts in A. C. circuits as if it were a *negative* inductance.

A good way to demonstrate this experimentally is by means of a double oscillograph (Fig. 482). A reactance coil is connected in an A. C. circuit, and the waves of the current and the voltage projected on a screen. The current wave appears in a certain position, lagging behind that of the e.m.f. by nearly 90 degrees. Substituting a condenser

for the reactance coil shifts the current wave by almost 180 degrees and makes it leading instead of lagging.

Another experimental proof is shown in Fig. 341. A reactance coil x is connected in phase 1 of a two-phase circuit, and the "wattless" power consumed in it measured by a wattmeter. The current and the voltage being displaced by almost 90 degrees, the wattmeter connected in the usual way would hardly give any indication at all. But connecting the potential coil of the wattmeter to phase 2, displaced by nearly 90 degrees, brings the two currents in the wattmeter almost into phase, and the instrument gives a considerable deflection. Now, if a condenser C is substituted for the reactance coil — without changing the wattmeter connections — it will be found that the wattmeter gives a *negative* deflection, so that it becomes necessary to reverse either its current or potential terminals. This shows that at the same point on the e.m.f. wave the currents through the inductance and through the capacity flow in the opposite directions. If current in the inductance is lagging, the capacity current must of necessity be leading.

These relations are represented vectorially in Fig. 342. The current i_x lags behind the voltage e_1 by a considerable angle; the capacity current i_c leads e_1 by almost 90 degrees. With regard to the voltage e_2 in the second phase, the two currents flow practically in opposite directions; this is the reason why the wattmeter terminals must be reversed in the above experiment when changing from an inductance to a capacity.

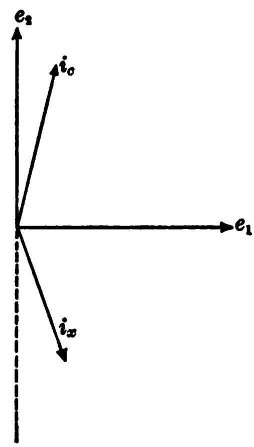


FIG. 342. Current and voltage relations, according to Fig. 341, shown vectorially.

When capacity and ohmic resistance are connected in series or in parallel, current and voltage relations and equivalent impedances may be determined from the triangles shown in Figs. 108 and 117, keeping in mind that capacity reactance y may be considered as a negative magnetic reactance x. The following experiment gives an example of these relations.

439. EXPERIMENT 21-C. — Capacity and Resistance in Parallel. — The connections are the same as in Fig. 120, save that a condenser of variable capacity is substituted for the reactance x. This corresponds to the practical case of a transmission line having an appre-

ciable capacity, and supplying power to a non-inductive load. Keep the resistance constant and gradually increase the capacity; read component amperes, total amperes, volts and watts. Repeat the same experiment with different values of resistance and of voltage, and at a different frequency. Measure — with direct current — the values of resistances used.

Report. Plot to microfarads capacity as abscissæ the curves shown in Fig. 343. Check the following relations: (a) Total current must be

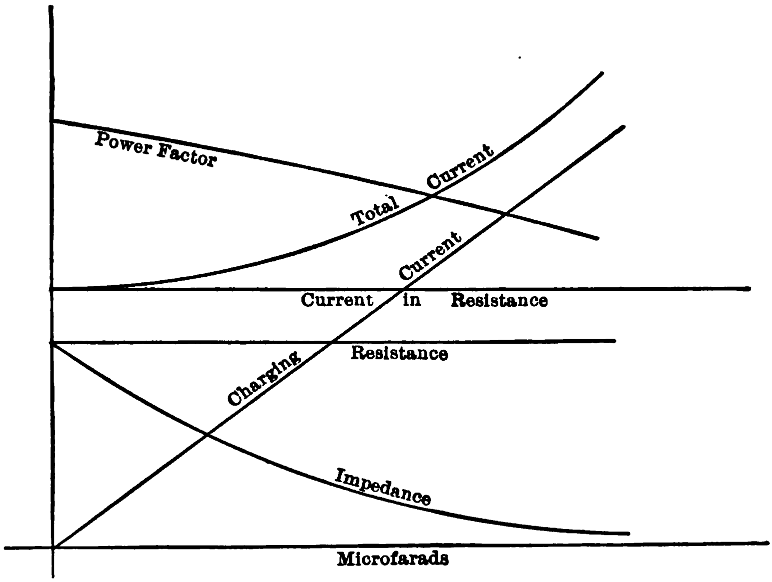


FIG. 343. Electrical relations with a resistance and a capacity connected in parallel to an alternating-current supply.

a geometrical sum of the component currents, as in Fig. 117. (b) Power factor calculated from wattmeter readings must be the same as determined from the triangle of amperes. (c) Wattmeter readings must check with the calculated i^2r. (d) The charging current must satisfy the expression (2), in § 436.

ELECTRIC RESONANCE.

440. Peculiar electrical relations arise in A. C. circuits, when capacity and inductance are present simultaneously. The phenomenon manifested is an abnormal rise of current, or of voltage, in part of the circuit, sometimes far above the values supplied by the source of power. This

is due to the neutralizing effect of capacity on inductance, and vice versa (§ 438); the phenomenon is called *electric resonance*. The name is derived from a similar phenomenon of mechanical vibrations produced by the inertia and the elasticity of a system. It has been pointed out in § 96 that inductance is analogous to mechanical inertia, while electric capacity may be likened to elasticity (see mechanical analogy in § 426). Thus, a certain combination of inductance and capacity gives rise to electrical oscillations of a definite frequency. If the frequency of the supply happens to be a submultiple of or is equal to that of these natural oscillations, the latter are greatly intensified, producing what is called the electric resonance.

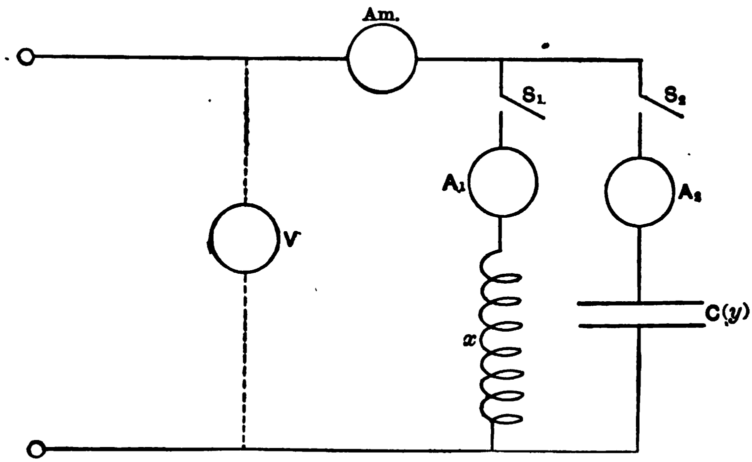


FIG. 344. Conditions necessary for producing a current resonance.

The phenomenon is different according to whether inductance and capacity are connected in parallel or in series. When they are in parallel (Fig. 344), current resonance is produced; when they are in series (Fig. 347), voltage resonance is the result.

441. Current Resonance. — In the experiment illustrated in Fig. 341 capacity and reactance were supposed to be connected to the supply in succession, the currents being represented in Fig. 342. Should both be connected to the line, as in Fig. 344, the current in the main line becomes smaller than that in either branch. This is because the line current is the geometrical sum, or the short diagonal of the parallelogram built on i_x and i_c. Thus we obtain a seemingly paradoxical result, that either of the component currents is larger than their sum.

This is actually observed when both switches S_1 and S_2 are closed at one time. In the ideal case, when no ohmic resistance is present, the current in the reactance is lagging 90 degrees behind the voltage, and is equal to $E \div x$. The current in the condenser is equal $E \div y$, and leads the voltage by 90 degrees. The line current i is the difference of the two, or

$$i = \frac{E}{x} - \frac{E}{y} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

When the magnetic impedance and the capacity impedance are equal to each other, in other words, when $x = y$, the line current i is reduced to zero, while a large current may circulate between x and C. The line voltage merely determines the value and the frequency of the resonance current, without actually supplying it. The condition $x = y$ means

$$2\pi nL = \frac{10^6}{2\pi nC} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

or

$$\sqrt{LC} = \frac{10^3}{2\pi n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In this formula L is in henrys, C in microfarads, and n in cycles per second. For instance, with $C = 50$ mf. and $n = 60$ cycles per second, perfect resonance takes place at a value of L deduced from the equation

$$L = \frac{1}{50}\left(\frac{1000}{2\pi.60}\right)^2,$$

or

$$L = 0.14 \text{ henry.}$$

With this value of inductance

$$\text{magnetic reactance } x = 2\pi \times 60 \times 0.14 = 52.8 \text{ ohms;}$$

$$\text{capacity reactance } y = \frac{10^6}{2\pi.60.50} = 52.8 \text{ ohms;}$$

the two being equal. Let the applied voltage be 220 volts; the current through the magnetic reactance

$$i_x = 220 \div 52.8 = 4.17 \text{ amp. (lagging);}$$

the current through the capacity reactance

$$i_y = 220 \div 52.8 = 4.17 \text{ amp. (leading).}$$

The total line current

$$i = i_x - i_y = 0.$$

Let the inductance now be 0.09 henry; the magnetic reactance

$$x = 2\pi . 60 \times 0.09 = 33.9 \text{ ohms},$$

and

$$i_x = 220 \div 33.9 = 6.5 \text{ amp.}$$

The total line current

$$i = 6.5 - 4.17 = 2.33 \text{ amp. (lagging).}$$

The line current is less than each of its components; this is a partial current resonance.

The relations become more complicated when ohmic resistance is present in either branch. The currents are then displaced less than 90 degrees from the line voltage and must be added geometrically. The diagram shown in Fig. 345 corresponds to the case when magnetic reactance remains constant, while the capacity is gradually increased. When the charging current is I_c', the resultant current I' in the line is lagging behind the impressed e.m.f. With a large capacity current I_c''' the resultant current I''' is leading. At a certain value I_c'' of the capacity current the total line current I'' is in phase with the e.m.f., as if the circuit possessed no inductance or capacity. The same relations are shown in Fig. 346 in the form of curves. As the capacity is increased, the line current first drops, then increases again as it becomes leading.

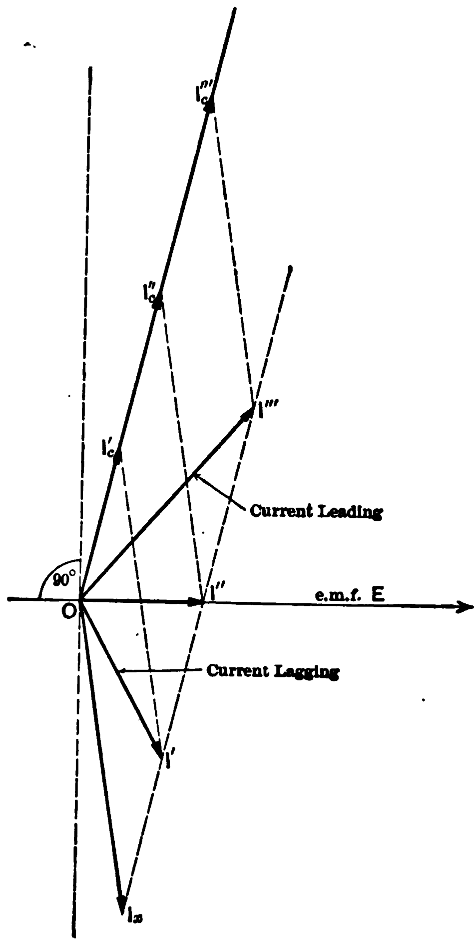


FIG. 345. A vector diagram showing current resonance.

442. EXPERIMENT 21-D. — Capacity and Reactance in Parallel. — Current Resonance. — The connections are shown in Fig. 344; it is well to have a wattmeter in the circuit, so as to be able to calculate the power factor of the line current. Close the switch S_1 and adjust the reactance current to a desired value. Then close S_2 and gradually increase the capacity. Read component amperes (in A_1 and A_2), total amperes, volts and watts. Note that the total current decreases and then increases again. Instead of using three ammeters, it may be more convenient to use one ammeter, and a polyphase board (§ 49).

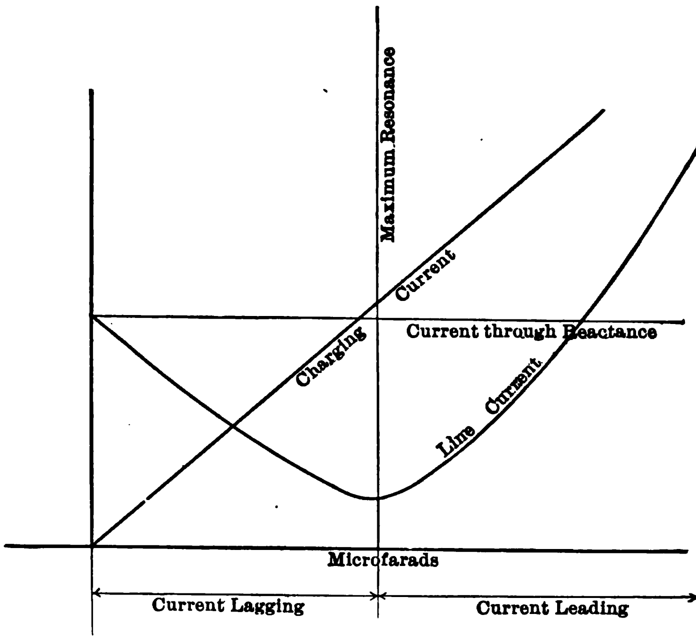


FIG. 346. Curves illustrating the gradual rise of current resonance.

Introduce some resistance in series or in parallel with the inductance, and repeat the same test. Also shunt the condenser with some resistance. Finally insert resistance in both branches, always taking readings with a gradually increasing capacity.

Report. Plot the results as shown in Fig. 346; construct several diagrams as in Fig. 345 and check the angles with those calculated from the wattmeter readings. See how closely the values of charging current check with those calculated from the expression (2) in § 436; also if equation (6) is satisfied when the capacity current is equal to the current through the reactance.

443. Voltage Resonance. — We shall now consider the resonance

produced by a reactance x and a condenser C connected in series (Fig. 347) in an A. C. circuit; the resistance r may at first be left out of consideration (r equal 0). Let a certain current i flow through the system; the voltage across the reactance leads the current by 90°; the voltage across the condenser lags behind it by the same amount. This means that the waves of voltage across MN and across PQ are opposite and partly neutralize each other. Therefore, the total voltage MQ is smaller than one of the component voltages, either across the reactance, or across the condenser. It may also be smaller than either of them. This peculiar condition is called *voltage resonance.*

An example may make this clearer. Let the magnetic reactance have a value of 10 ohms and the capacity reactance be 2.5 ohms, both values at a frequency of 60 cycles per second. The equivalent reactance is $10 - 2.5 = 7.5$ ohms.

At a terminal voltage of 150 volts between M and Q, the current is $= 150 \div 7.5 = 20$ amperes. The drop across the magnetic reactance is

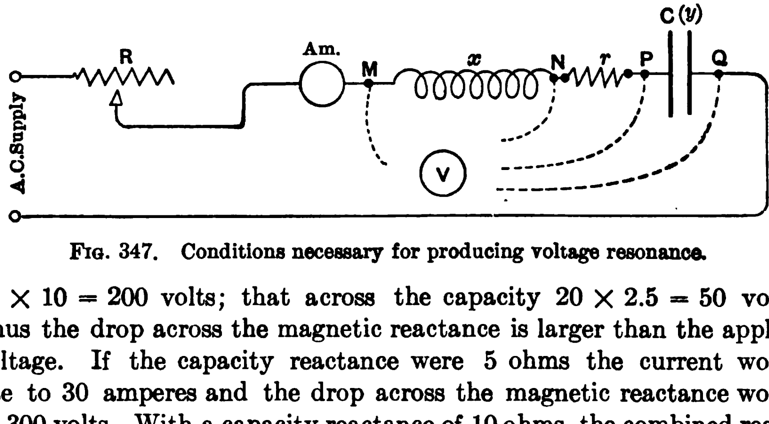


FIG. 347. Conditions necessary for producing voltage resonance.

$20 \times 10 = 200$ volts; that across the capacity $20 \times 2.5 = 50$ volts. Thus the drop across the magnetic reactance is larger than the applied voltage. If the capacity reactance were 5 ohms the current would rise to 30 amperes and the drop across the magnetic reactance would be 300 volts. With a capacity reactance of 10 ohms, the combined reactance becomes zero; the current and the voltage rise indefinitely. When such a combination actually happens either the condenser breaks down, or the inrush of current opens the circuit-protecting device.

Reducing the capacity still further, or, which is the same, increasing the capacity reactance, makes the voltage drop across the condenser larger than that across the reactive coil. For instance, with a capacity reactance of 15 ohms the equivalent reactance becomes $15 - 10 = 5$ ohms, and the current 30 amperes; in this case the current is leading. The voltage drop across the condenser becomes $30 \times 15 = 450$ volts.

Instead of varying the capacity, a perfect resonance could be obtained by changing the frequency. Let us assume again the same values of

reactances, 10 ohms and 2.5 ohms at 60 cycles per second. At a frequency of 30 cycles, the equivalent reactance becomes

$$10 \div 2 - 2.5 \times 2 = 0.$$

The current and the voltage rise indefinitely.

444. Vector Diagrams of Voltage Resonance. — Resonance is made less harmful in practice, due to the presence of some resistance r (Fig. 347), — resistance limits the inrush of current and the rise of potential. Assume that the resistance r and the reactance x remain constant, while the capacity C is being gradually increased. This makes both the current in the line and the voltage across MQ vary. To make the conditions more definite we shall consider two limiting cases: (1) line current kept constant; (2) line voltage kept constant. The regulation of current and voltage is made by the rheostat R.

(*a*) *Line current constant* (Figs. 348 and 349). The drop $OA = ix$ in the inductive reactance is leading the vector of the current by 90°. The ohmic drop $AB = ir$ is in phase with the current. The drop $BE' = iy$ in the capacity is lagging behind the current. The total voltage across the combination of the three is represented by the vector $OE' = iz$, where z is the equivalent impedance of the circuit. From the figure $OABE'$

$$z = \sqrt{(x - y)^2 + r^2},$$

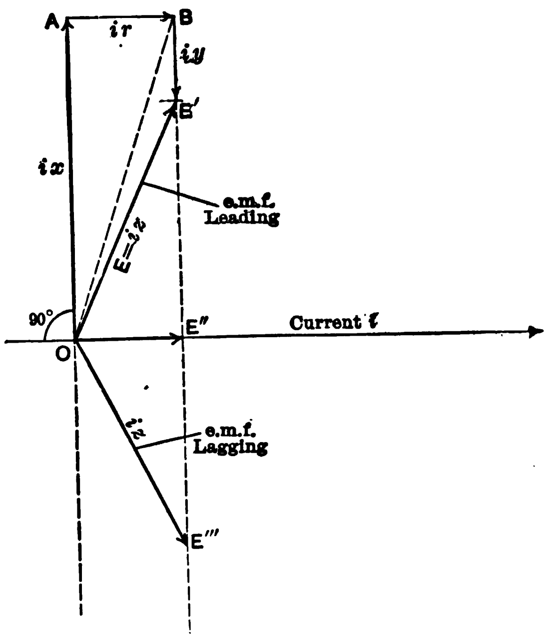


FIG. 348. Vector diagram of voltage resonance, at a constant current.

the capacity reactance y opposing the magnetic reactance x. The current is lagging behind the line e.m.f. the action of the inductance being preponderant. With a larger capacity reactance (smaller capacity) the drop across the condenser may become as large as BE'''.

The applied voltage becomes OE''', the current being in this case leading. The equivalent reactance z of the circuit may have the same value as before, except that $(y - x)$ must be used instead of $(x - y)$.

At a certain value of capacity, the drop across it becomes equal to the drop across the reactance x, and the resultant e.m.f. OE'' is in phase with the current. The line voltage is, in this case, just sufficient for overcoming the ohmic resistance ($OE'' = ir$); the capacity and the inductance neutralize each other. If the circuit contained no resistance, the current and the voltage would rise indefinitely.

Thus with variations of capacity, the extremity of the vector of the

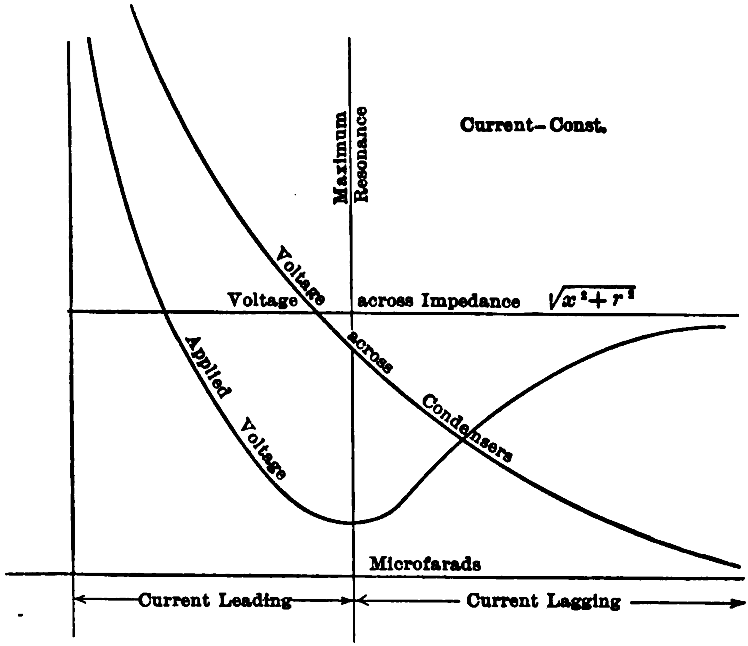


FIG. 349. Curves of voltage resonance at a constant current, as per Fig. 348.

applied voltage travels on BE''', the current being lagging for large values of capacity (small values of y), and vice versa. The corresponding relations are plotted in Fig. 349.

(b) *Line voltage constant* (Figs. 350 and 351). The polygon $OA'B'E'$ is the same as $OABE'$ in Fig. 348. The current being variable, the triangle of drop $OA'B'$ increases and decreases with the value of the current, remaining similar to itself. At the same time, the point E' moves on the circle drawn with the line voltage E as a radius; the assumption being that the line voltage is maintained constant by means of the rheostat R (Fig. 347).

For small values of capacity (large values of y) the figure assumes the position $OA'''B'''E'''$, the current becoming leading. At a certain value of capacity, such that $x = y$, the e.m.f. $= E''$ is in phase with the current, as if the circuit consisted of ohmic resistance r only. The relations are represented by the curves in Fig. 351.

445. EXPERIMENT 21-E. — Capacity and Reactance in Series. — Voltage Resonance. — The connections are shown in Fig. 347;

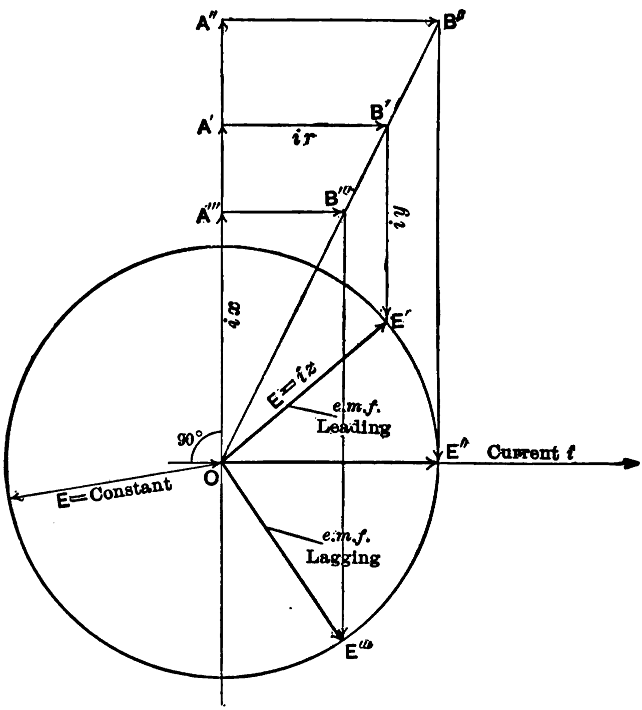


FIG. 350. Voltage resonance at a constant applied voltage.

it is well to have in addition a wattmeter for determining the phase displacement between the line voltage and the current. First try a resonance in its pure form, without the resistance r. Introduce enough resistance R in the circuit so that the current would not exceed a predetermined value, even when $x = y$; or else protect the circuit by a reliable circuit-breaker. Connect in as much capacity as possible, and a large inductive reactance, so as to have a rather small lagging current. This corresponds to the right end of the curves in Fig. 351. Gradually reduce the inductive reactances measuring voltages across x and across

C; also the line voltage and the current. The voltage curve (Fig. 351) rises very abruptly; therefore the student should be careful not to break down the insulation of the condenser. When the limit is reached, open the circuit and reduce the reactance x considerably beyond the resonance point, so as to have a small leading current; approach the point of maximum resonance from the other side.

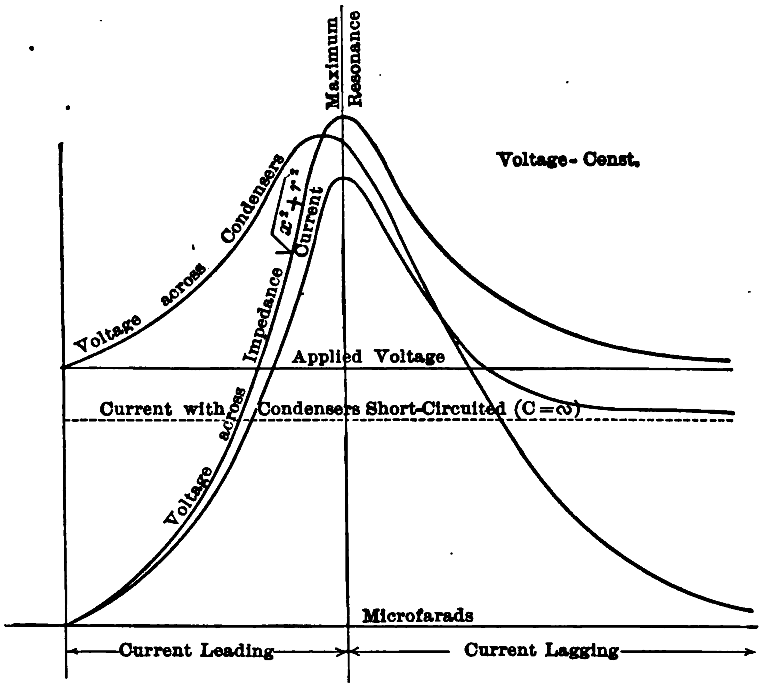


FIG. 351. Curves of voltage resonance at a constant applied voltage, as per Fig. 350.

Now connect some resistance r, such as to give, say, 10 to 20 per cent ohmic drop at the desired current; take curves shown in Fig. 349, that is to say, keeping the line current constant. Keep the resistance r and the reactance x constant and vary the capacity within as wide limits as possible. Finally short-circuit the condenser to realize the limiting condition with an infinitely large capacity (horizontal line in Fig. 349). Perform a similar test, keeping the terminal voltage constant (Fig. 351).

Report. Plot curves, as in Figs. 349 and 351; check some of the results by means of diagrams shown in Figs. 348 and 350.

CHAPTER XXII.

TRANSMISSION LINES.

446. ELECTRIC power is usually generated in places more or less remote from where it is used; therefore a *transmission* line is a necessary link between the generating station and the current-consuming devices. Where current is consumed in many places, as, for instance, in the various houses of a town, wires supplying power to separate houses constitute the *distributing* network, to which the transmission line is connected at suitable places. Strictly speaking, there is no marked distinction between a transmission line and a distributing line; the subdivision is introduced here merely to indicate simple lines with

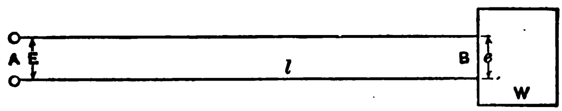


FIG. 352. A simple diagram of electric power transmission.

power consumption at the end only (transmission lines), and complicated networks of conductors with power tapped off at different places (distributing lines). A transmission line may be compared to a trunk railway, delivering goods at the end only; while distributing lines are analogous to a system of local branched railways, delivering goods at a great many places within a comparatively small area. Electrical properties of distributing lines are considered in Chapter XXIII.

447. Formula for Voltage Drop. — The problem of electrical relations in a direct-current transmission line, in its simplest aspect, may be represented thus: W kw. (Fig. 352) are to be delivered at B, which is l miles distant from a power house situated at A; the pressure at B must equal e volts. The pressure E at A must be somewhat higher, to compensate for the loss in the line. It is required to compute the cross-section of the line conductors. This cross-section depends on the loss allowed in the line: the larger the permissible loss or drop of pressure, the smaller and less expensive becomes the line. There are, however, several limitations as to the allowable loss in the line; these are discussed in § 448.

Generally speaking, the problem is solved by merely applying Ohm's law to the given case; but for practical purposes this general law can be reduced to more specific expressions, which bring into prominence the relations between the voltage drop and the cross-section of the line. Let the resistance of a wire 1 foot long and having a cross-section of one circular mil be ρ ohms; then the resistance of a single wire l feet long and of a cross-section of q circular mils will be

$$\frac{\rho l}{q}$$

The line current $i = W \div e$, so that total voltage drop in the line is

$$\frac{2\rho li}{q} \text{ or } \frac{2\rho lW}{qe}$$

Let p be per cent drop, or the ratio of the voltage drop in the line to the receiver voltage e. From the above formula it follows that

$$p = \frac{200\,\rho l W}{qe^2}.$$

Two unknown quantities usually enter into the practical problems: the cross-section q of the wire, and the permissible voltage drop p. From the above formula the product

$$pq = \frac{200\,\rho l W}{e^2} = \frac{200\,\rho l i}{e} \quad \text{. . . . . (1)}$$

can be figured out for any given case; the selection of the proper values for p and q is left to the sound judgement of the designer. In this selection he is guided by the three considerations discussed in the next article: voltage regulation, energy loss, and the limit of temperature rise. Here, as in most practical problems, an infinite variety of solutions are possible; engineering skill, feeling, and previous experience have to supply the lack of exact mathematical relations.

448. Practical Limits of Voltage Drop. — The principal considerations to be kept in mind when selecting the per cent drop p in the formula (1) are:

(1) *Voltage regulation at the receiver end.* The higher the loss in the line the more difficult it becomes to maintain constant voltage at B when the load varies. The drop in the line is proportional to the load, so that at full load the voltage at B may be considerably lower than that at A, while at light loads the two voltages are approximately equal to each other. As the switchboard attendant in the power house

cannot always follow the fluctuations of the load and adjust the voltage, the pressure at B varies with the load. If the voltage drop and fluctuations of pressure exceed a certain limit, the line gives a poor service, particularly for incandescent lamps.

The per cent difference in voltage (at the receiving end of the line) at full load and at no load is called *the regulation of the line.* Suppose the voltage at the receiving end to be 200 volts at full load, and assume the voltage drop in the line itself to be 14 volts; the generator voltage is then 214 volts. When the load is thrown off and the same generator voltage kept as before, the voltage at the receiving end rises to 214 volts. By definition, the regulation of the line is

$$\frac{214 - 200}{200} = 7 \text{ per cent.}$$

(2) *Energy loss in the line.* The higher the loss allowed in the line the smaller is the original investment in the line copper; but this is counter-balanced by a continual loss of energy in the line. If the price of coal is high, it may be cheaper in the end to use a large cross-section of conductors, in order not to lose too much energy as I^2R heat in the line. If cheap and abundant water-power is available, a smaller cross-section may be more economical. The most economical cross-section and loss in the line must be determined in each case separately, according to the local conditions.

(3) *Temperature rise in conductors.* Having determined the cross-section of the conductors so as to satisfy the two above-named conditions, it still remains to determine if the conductor selected can carry the current without excessive heating. The smaller the cross-section the less current the conductor can carry safely. The safe carrying capacity of couductors has been determined by experiments; the results are given in various engineering pocket-books, in Fire Underwriters' Rules, etc. If the conductor selected is too small for the current, one of the next larger sizes of wire must be taken, which can stand the current without excessive heating.

449. Factors Influencing Voltage Drop in Transmission Lines. — Formula (1) shows that the voltage drop p depends on five variables:

(1) Load W;
(2) Length l of the line;
(3) Its cross-section q;
(4) Transmission voltage e;
(5) Specific resistance ρ of the material.

The influence of each of these factors should be studied separately. The first two factors are considered in Experiment 22-A; the next two in Experiment 22-B. This subdivision is made because voltage drop *increases* with the load and with the length of the line (Fig. 354), and *decreases* with the increase in cross-section and the voltage (Fig. 355). The influence of the material may be investigated in connection with either experiment.

In alternating-current transmission lines, voltage drop depends, in addition, upon

(6) Power factor of the load;
(7) Inductance and capacity of the line itself.

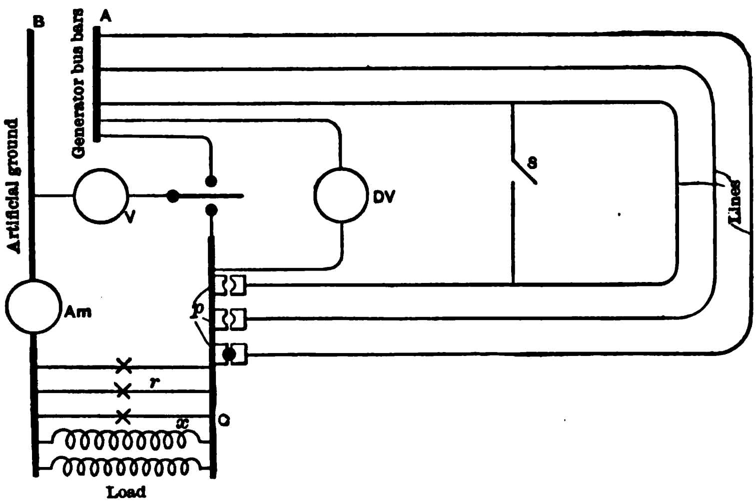


FIG. 353. A laboratory arrangement for studying electrical relations in transmission lines.

The influence of these two factors is studied in Experiments 22-D, 22-E, and 22-F.

450. Experimental Lines. — The practical import and the physical meaning of the deductions made in §§ 447 and 448 can be best studied on a few experimental lines strung in the laboratory. The materials used in actual lines are copper and aluminum. These should be replaced in the laboratory lines by iron and German silver wires which have a considerably higher resistance; this is necessary in order to obtain a sufficiently large voltage drop on comparatively short distances.

A convenient arrangement of experimental lines is shown in Fig. 353. The lines form a loop, so that the generating and the receiving

end are brought together. The drop along the line is read directly on the low-scale voltmeter *DV*. One of the line wires is replaced by a bus-bar of negligible resistance (artificial ground), in order to simplify the measurements. Any desired number of lines may be provided between the generator and the receiver bus-bars, and each may be used by inserting the plug in one of the receptacles *p*. A voltmeter *V* is provided for measuring the pressure at the two ends of the line. The ammeter *Am* in the return bus-bar measures the line current. An indicating wattmeter may be connected into the circuit, if desired; its current winding must be in series with the ammeter, and the potential winding either across the load, or across the generator bus-bars.

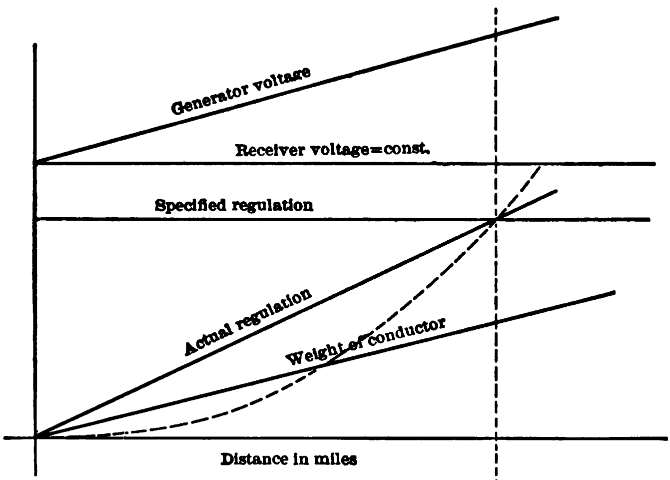


FIG. 354. Influence of distance of transmission on voltage regulation of a transmission line.

The voltage of the supply is regulated either by the field rheostat of the generator, or by a rheostat in series with the line. A short-circuiting switch *S* is provided for changing the length of one of the lines, if desired.

The influence of the seven factors enumerated in § 449 may be conveniently studied on this model.

451. EXPERIMENT 22-A. — Influence of Load and of Distance of Transmission on Voltage Regulation of a Line. — The purpose of the experiment is to verify some of the relations expressed by formula (1) in § 447. The experimental lines may be conveniently arranged as in Fig. 353; some of the results are plotted in Fig. 354.

The voltage at the receiver end is kept constant; the load is varied from zero to a practicable maximum. Read amperes, volts at both ends, and the voltage drop along the line on the low-scale voltmeter *DV*. Take two or three other lines of the same material and same cross-section, but of a different length; repeat the same test. Finally perform a similar test on a line of different material. Before leaving the laboratory measure the cross-section and the lengths of the lines experimented upon; ascertain the material of which they are made.

Report. Plot, for each line, to amperes load as abscissæ: voltages at the generator and the receiver ends; also, to a larger scale, the difference of these voltages, from the readings on the low-scale voltmeter. Plot

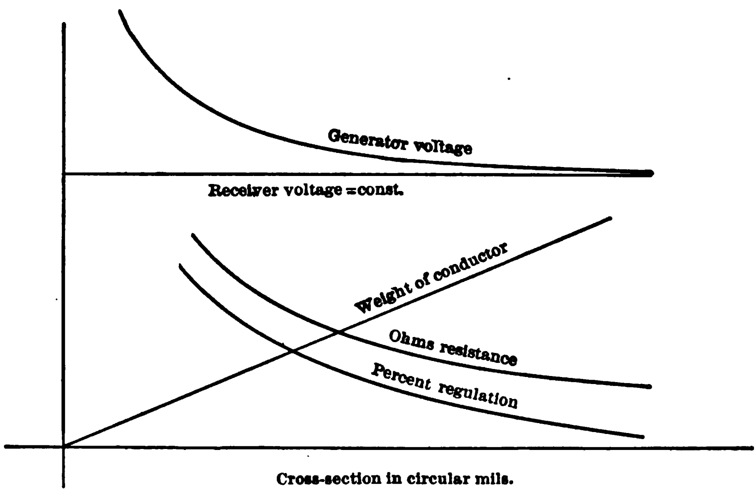


FIG. 355. Influence of cross-section of a transmission line on its voltage regulation.

per cent regulation as explained in § 448. Combine these curve sheets into one, as shown in Fig. 354, for the largest load used during the experiment. Take per cent regulation of the longest line and figure out the weights of shorter lines, which would give the same per cent regulation. The result is a parabola, shown by dotted lines. Explain that the weight, or the cost of the line conductor increases as the square of its length, with the same load and the same per cent regulation. For one of the lines figure out ρ from formula (1); check the value obtained with that given for the same material in engineering pocket-books.

452. EXPERIMENT 22-B. — Influence of the Transmission Voltage and of the Cross-Section of a Line on its Regulation. — This experiment is similar to the preceding one, save that the trans-

mission voltage and the cross-section of the line are varied, while the load and the length of the line are kept constant.

Of the several experimental lines of the same length (Fig. 353), take the one having the smallest cross-section, and put on a certain load at the lowest practicable voltage. Read volts, amperes and voltage drop. Gradually increase the voltage at the generating end; at the same time reduce the line current, so as to keep kilowatts load constant. Repeat the same experiment on two or three lines of different cross-section and material. A greater variety of cross-sections is obtained by using two or more lines in parallel. Before leaving the laboratory, measure the cross-sections and the lengths of the lines experimented upon, and inquire about the material of which they are made.

Report. Plot to receiver voltages as abscissæ: generator voltage, line drop, per cent regulation (§ 448), line current. Verify, that the product pe^2 is constant for each curve, according to formula (1).

Combine the curve sheets into one for a certain value of the receiver voltage, as shown in Fig. 355. Add curves of weight and resistance of the line. Check the value of ρ obtained from the test data with the value given for the same material in engineering pocket-books.

453. Branched Transmission Lines. — In many cases power generated in a power house has to be transmitted to several localities. If independent transmission lines are used for each locality, the problem is solved for each transmission line separately. Sometimes, however, it is more economical to use a common transmission line for at least a part of the way (Fig. 356), and then divide it into several branches. Fig. 356 represents a case where power generated at A is transmitted by a common line to D, and thence branched to towns B and C.

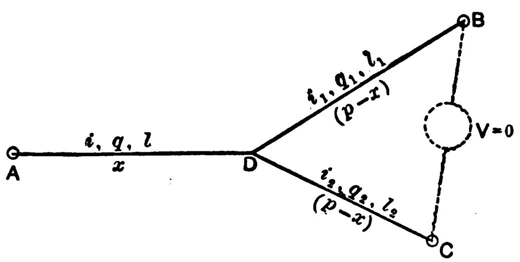


FIG. 356. Branched transmission line.

The problem here is to determine the cross-sections of the three parts of the transmission line, so that the weight of copper be a *minimum*, for a given total drop of voltage between A and C, or A and B. Assume as before the voltage at B (and at C as well) to be e, and the total drop between A and B to be p per cent, as before. The only unknown quantity is the per cent drop x between A and D; if this be

known, the per cent drop $(p - x)$ in the branches DB and DC will also be known; each conductor can then be calculated separately by the fundamental formula (1) given above. The drop x can be calculated as follows: On the basis of formula (1) we have:

$$xq = \frac{200\, i\rho l}{e} \qquad (2)$$

also

$$(p - x)\, q_1 = \frac{200\, i_1\rho l_1}{e};$$

and

$$(p - x)\, q_2 = \frac{200\, i_2\rho l_2}{e}; \qquad (3)$$

The total weight of the line conductors is proportional to

$$P = ql + q_1l_1 + q_2l_2;$$

substituting the values for q, q_1, q_2 from the above equations, we obtain:

$$\frac{P}{200} = \frac{i\rho l^2}{ex} + \frac{i_1\rho l_1^2}{e\,(p - x)} + \frac{i_2\rho l_2^2}{e\,(p - x)}.$$

The weight is a minimum, when $\frac{dP}{dx} = 0$, or

$$-\frac{il^2}{x^2} + \frac{i_1l_1^2}{(p - x)^2} + \frac{i_2l_2^2}{(p - x)^2} = 0,$$

whence

$$\left(\frac{x}{p - x}\right)^2 = \frac{il^2}{i_1l_1^2 + i_2l_2^2}.$$

This equation gives

$$\frac{x}{p - x} = \sqrt{\frac{il^2}{i_1l_1^2 + i_2l_2^2}} = a;$$

and finally

$$x = p \cdot \frac{a}{1 + a} \qquad (4)$$

where a is introduced for the sake of brevity. The drop x is calculated from this equation; the cross-sections of the three parts of the line are figured out from formulæ (2) and (3).

In checking these relations experimentally it is absolutely essential that the drop $A - B$ be the same as $A - C$, since this condition was presupposed to be fulfilled in deducing the rule of copper economy. In order to be sure that this is actually fulfilled during the test, it is

advisable to have a low-reading voltmeter connected between B and C (Fig. 356); the load is adjusted so that this voltmeter reads zero. Or else, a low-resistance wire can be connected between B and C, so as to equalize the voltages.

454. EXPERIMENT 22-C. — Rule of Minimum Copper in Branched Transmission Lines. — The experiment is intended to illustrate the relations derived in the preceding article. Several experimental lines, or ordinary resistances of uniform material, should be provided in the laboratory, and connected as in Fig. 356.

(a) Take a combination of three lines, and by trials so adjust the load in both branches that the condition (4) is approximately fulfilled. Vary the load in the two branches so, that the total drop p remains constant. Read volts, amperes and drops p and x. Note the value of q and l in the three branches. (b) Take another set of readings, keeping the total current i constant, but varying i_1 and i_2. (c) Repeat the same experiment under different conditions, viz., different lengths, different cross-sections of the lines, etc.

Report. Show from the first series of readings, that when (4) is fulfilled, maximum amount of power is delivered through a given line with the same drop p. From the second set of readings prove, that a given amount of power is delivered with the minimum drop in the line, when (4) is fulfilled.

ALTERNATING-CURRENT TRANSMISSION LINES.

455. The electrical relations deduced in § 447 for direct-current lines are modified in alternating-current lines by the influence of inductance and capacity, either in the load or in the line itself.* These factors will be taken up in detail in the following articles. All deductions that are made there, and the experiments specified, are for single-phase lines. The results may be applied to two- and three-phase lines, keeping in mind the following relations, deduced in Chapter XXV:

(a) A *two-phase line* can be considered as a combination of two independent single-phase lines, AA' and BB', each carrying one half of the load (Fig. 357). The cross-section of each conductor is only one half of what it would be for a single-phase line; but as there are four conductors instead of two, the total weight of the line is the same as with the single-phase line.

(b) A *three-phase line* can be considered as a combination of two lines, say AB and CB (Fig. 358), the conductor B being their common

* The following treatment presupposes on the part of the reader a knowledge of the fundamental relations established in Chapters V and XXI.

return wire. Therefore A and C need only have one half the cross-section of a single-phase line carrying the same total load W. The wire B must have the same cross-section as either A or C, because (in a three-phase system) the return current is equal to each of the line currents, and any of the three wires can be considered as a return wire. From this, it follows that total weight of the conductors in a three-phase line is but 75 per cent of the weight of an *equivalent* single-phase line.

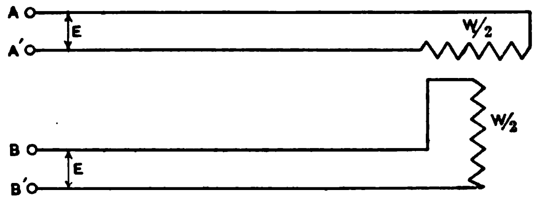


FIG. 357. A two-phase power transmission.

Thus, whether you have a three-phase or a two-phase line, figure the cross-section of the conductors, as if it were a single-phase line having the same total load W, the same distance of transmission and the same permissible voltage drop. Then, for polyphase transmission use wires of *one half* cross-section, — four wires for the two-phase line, three wires for the three-phase line (see also § 538).

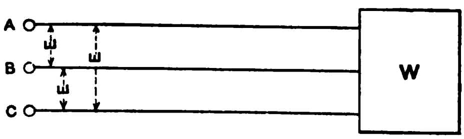


FIG. 358. A three-phase power transmission.

456. Influence of the Power Factor of the Load. — Assume first that the line has ohmic resistance only, but no inductance or capacity; let the load be partly inductive (see § 96). The relations expressed by the formula (1) for direct current may be represented here by the triangle OAB (Fig. 359). Let OB be the vector of the receiver voltage e, OC that of the current i, lagging behind the voltage by an angle ϕ, which depends on the properties of the load. The voltage drop ir in the line can be represented by a line BA parallel to the direction of the current vector OC; r is the total ohmic resistance of the line. The geometrical sum of OB and BA is equal to OA, and represents the voltage E in the power house. It will be seen from this diagram that the voltage drop, AB, in the line is subtracted *geometrically* from the station voltage E, instead of algebraically, as in the case of direct currents. From the triangle OAB, we have

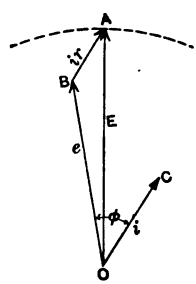


FIG. 359. Voltage drop in a transmission line, at a partly inductive load.

$$E^2 = e^2 + i^2r^2 + 2\,ire \text{ Cos. } \phi.$$

This formula, or the diagram, Fig. 359, takes the place of the simpler relations for direct-current lines. Suppose, for instance, that it is desired to figure the cross-section of a transmission line, under the condition that the power W is consumed at a given power factor $\operatorname{Cos} \phi$ and at a given voltage e; the voltage drop in the line must not exceed p per cent of e. First determine the line current $i = \dfrac{W}{e \operatorname{Cos} \phi}$; then construct OB and OC, and from O strike an arc of a circle with a radius $E = (1 + p/100)\ e$. Draw the line BA parallel to OC; the point A of its intersection with the arc gives the length $BA = ir$. Knowing i, the resistance r of the line can thus be determined, and the cross-section of the conductor found from the familiar formula

$$r = \frac{2bl}{q}.$$

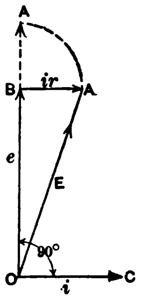


FIG. 360. Voltage drop in a transmission line at a totally inductive load.

It will be seen from Fig. 359 that in case of an inductive load, per cent voltage drop $AB \div OB$ and per cent regulation $\dfrac{(OA - OB)}{OB}$ are different. Take, for instance, the extreme case of a purely inductive load (Fig. 360), and suppose that the line drop BA is equal to 30 per cent of OB. Then the voltage E in the power house

$$\begin{aligned} OA &= \sqrt{e^2 + (0.30\ e)^2} \\ &= e\sqrt{1.09} = 1.044\ e; \end{aligned}$$

in other words, the difference between E and e, or the regulation, is 4.4 per cent, while the line drop is 30 per cent. If the load were non-inductive the voltage E should be 30 per cent higher than e, as shown by the vector OA'.

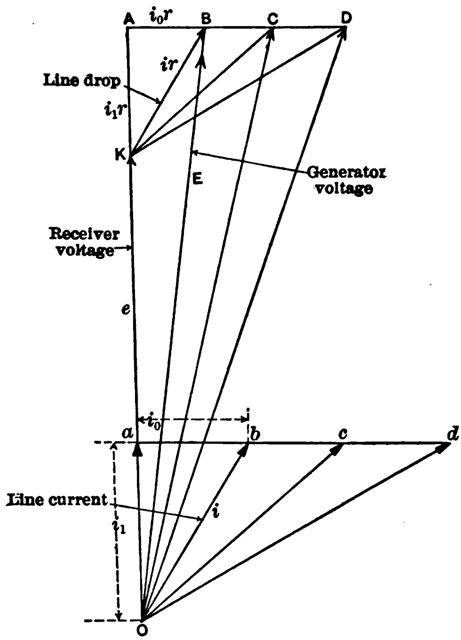


FIG. 361. Influence of the power-factor of the load on the voltage drop in a transmission line.

This should not be understood, however, in the sense that the lower the power factor the more favorable are the conditions for transmitting power. On the

contrary, a lower power factor means a higher current *with the same power transmitted;* therefore, a larger line drop and a larger I^2R loss; this case is taken up in the next article.

457. Constant Power Transmitted at Different Values of Power Factor. — A diagram corresponding to this case is shown in Fig. 361: the curves in Fig. 362 illustrate the result. $Ob = i$ again represents the line current. It consists of the working (or power) component $Oa = i_1$, which is in phase with the voltage $OK = e$ at the terminals of the load, and of the wattless component $ab = i_0$ perpendicular to OK. The

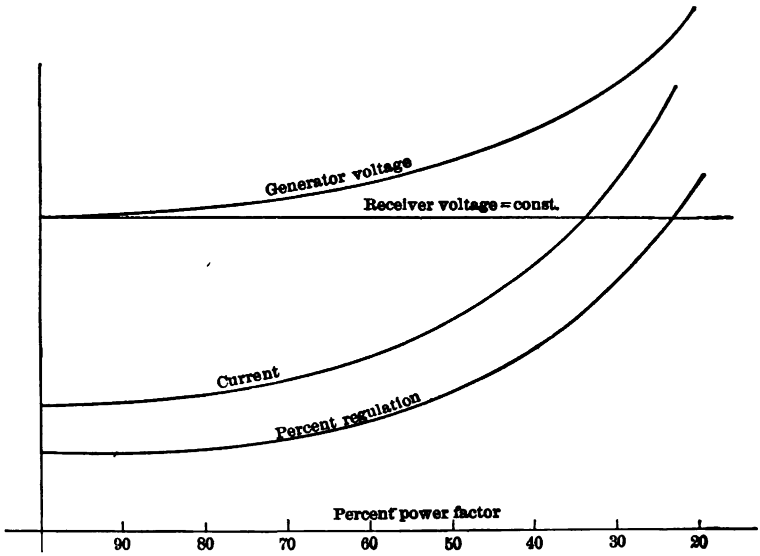


FIG. 362. Curves showing the effect of a varying power factor of the load on the regulation of a transmission line.

vector $KB = ir$ of the voltage drop in the line is parallel to i; OB represents the generator voltage E.

If the power delivered to the load is constant, the working component $Oa = i_1$ is constant. Changes in total current i are caused by variations in the wattless component, which becomes, successively, ac, ad, . . as the power factor of the load decreases. The corresponding voltage drop in the line also increases, and assumes the values KC, KD. The generator voltage becomes OC, OD, . . . At a power factor of 100 per cent, total current i is equal to the working component i_1; line drop is represented by KA, the generator voltage $= OA$.

The values of OB, OK and Ob are plotted in the form of curves in Fig. 362; the regulation curve gives per cent increase of OB over OK.

458. EXPERIMENT 22-D. — Influence of the Power Factor of the Load on Voltage Regulation of a Transmission Line. — The experiment may be arranged as in Fig. 353, or as in Fig. 363; in the latter figure the reactance x in the line should be omitted. Iron wires should not be used for this experiment, as they give an appreciable reactance effect, which destroys the value of the results. Use copper or German silver wires.

(a) Apply a certain load at as low a power factor as possible. Read volts at both ends of the line, and, if possible, the voltage drop along the line itself; also load amperes and watts. *Keep watts constant,* and gradually reduce the wattless current by increasing the reactance of the load connected across the line, until a power factor of 100 per cent is reached. This condition is practically obtained when the load con-

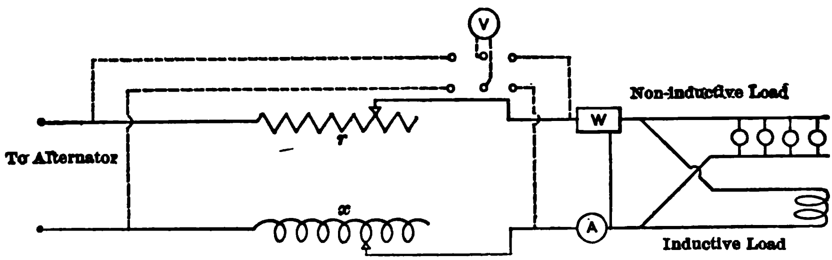


FIG. 363. Diagram of connections for studying the effect of inductance and of resistance in the transmission line and in the load.

sists of incandescent lamps only. Repeat a similar run with a different resistance of the line, and then with a different load.

(b) Now reëstablish the first conditions and vary the load *so as to keep total amperes constant,* gradually increasing watts. Repeat a similar run with a different resistance of the line, and then with a different load.

Report. Plot curves, as in Fig. 362; check some of the results by constructing diagrams, similar to those shown in Figs. 359 and 361.

459. Influence of Inductance in the Line. — Inductance in transmission lines is caused by the magnetic flux embraced within the loop formed by line conductors. The influence of this inductance is noticeable on long, high-tension lines with considerable distance between the wires. Inductance and ohmic resistance are distributed along the line; but for experimental purposes it is more convenient to have them separated, as in Fig. 363.

The voltage relations, shown in Fig. 359, must be modified into those in Fig. 364, in order to take into account the inductance of the line.

$OK = e$ is the receiver voltage, i is the line current, lagging behind it by an angle ϕ, which depends on the properties of the load. The drop KL in the line consists of the ohmic drop $KM = ir$, parallel to i, and of the inductive drop $ML = ix$ perpendicular to i. The generator voltage E is represented by the vector OL.

With lines having but a few per cent drop, the triangle KLM becomes too small to allow the difference between E and e to be measured with a sufficient accuracy. In such cases it is preferable to figure out E analytically. By completing the triangle OLN we have:

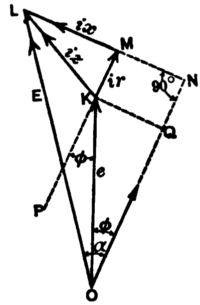


FIG. 364. Vector diagram corresponding to the connections in Fig. 363.

$$E^2 = (e \operatorname{Cos} \phi + ir)^2 + (e \operatorname{Sin} \phi + ix)^2 \quad . \quad . \quad . \quad (5)$$

from which E can be calculated.

It will be seen from Fig. 364 that per cent regulation, or the difference between E and e, depend not only on the current, but also on the power factor of the load. It may be shown by constructing a few diagrams, that a line with a comparatively high inductance may regulate satisfactorily on non-inductive loads, but give a poor regulation on inductive loads, and vice versa (see Fig. 360).

460. EXPERIMENT 22-E. — Voltage Drop in Lines having a Considerable Inductance. — (a) Begin the experiment (Fig. 363) with a line having negligible ohmic resistance, but a considerable reactance. The latter is conveniently provided for laboratory purposes by a coil of wire, with a movable iron core inside. Take a highly inductive load and adjust the conditions so as to have a difference of from 10 to 15 per cent between the generator voltage and the load voltage. Keep the current constant, and gradually raise the power factor of the load by increasing the non-inductive portion and decreasing the inductive portion of the load. Read the voltages and the voltage drop, amperes, and watts, until the load becomes entirely non-inductive. (b) Repeat the same experiment with a line having ohmic resistance only, and giving the same difference in voltage. (c) Finally test a line possessing both ohmic and inductive resistances in about equal proportion.

Report. Plot the results to power factor of the load as abscissæ (compare Fig. 362). Construct a few diagrams, as in Fig. 364, for low values of power factor, and check by means of them the results obtained at higher values of power factor. Explain the difference in regulation

obtained with the lines having large and small inductive drop, at different values of power factor.

461. Influence of Capacity in Transmission Lines.* — Let *I* in Fig. 365 represent the generator end, *II* the receiver end of a transmission line, and *C* its electrostatic capacity. This capacity in reality is uniformly distributed along the line, but, for the sake of simplicity, may be assumed to be concentrated at one point. The generator has to supply not only the load current, but also a leading wattless component, or charging current. This capacity effect takes place independently of the load. There are cases known on long high-tension transmission lines, where this capacity effect amounts to over 1000 apparent kilowatts; this means that a large generator has to run at practically its full ampere output, without supplying any actual load at the receiver end.

Inductance, as a rule, is an undesirable element of the load, because it produces a lagging wattless current and lowers the power factor.

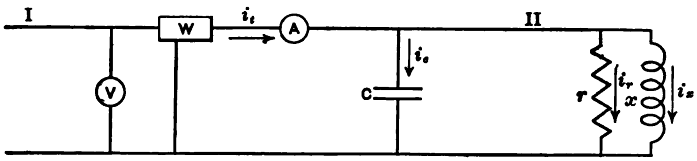


FIG. 365. Capacity, inductance, and resistance in parallel.

However, in the case under consideration, inductance *improves* the power factor at the generating station, since the lagging component compensates for the leading capacity current (§ 441).

This principle also furnishes a practical means of obtaining this compensating effect when the line is comparatively short and the voltage not very high, but the load is highly inductive (motors and transformers running at light load). Then the capacity effect is small, while at the same time the line carries considerable lagging currents. The power factor can be improved by connecting across the line an apparatus which draws a leading current, and consequently neutralizes the lagging component. Ordinary condensers are too expensive, and not reliable enough on high voltages, to be used for such a purpose. A large over-excited synchronous motor (§ 551) is quite often used for correcting low power factor in a transmission line. It takes in a leading current, and thus compensates for the lagging currents of the rest of the system. The generating station has to supply the power component of the cur-

* For the fundamental properties of electrostatic capacity the reader is referred to Chapter XXI.

rent only. For further details in regard to current and voltage resonance, see §§ 440 to 445.

462. EXPERIMENT 22-F. — Influence of Capacity in Transmission Lines. — (a) Take a line, as in Fig. 365 (or Fig. 353), possessing ohmic resistance only; connect some capacity across it at the middle point between the generator and the load. Select a load at a power factor, say between 60 and 80 per cent. Gradually increase the capacity, keeping the load constant. Read load current, capacity current and total current; generator volts, load volts, and the volts across the condensers. When varying the load be careful not to obtain conditions which might give a dangerous current or voltage resonance. Repeat a similar run with the same load current, but at a power factor of 100 per cent; then at a power factor as low as obtainable.

Adjust conditions so that the influence of capacity is particularly noticeable, and distribute the same capacity in two, three or four points along the line, instead of having it concentrated at one point. See how this affects the regulation of the line.

(b) Perform a similar experiment with a line having inductance, instead of resistance. Produce voltage resonance (§ 443) under conditions which may occur on actual transmission lines. In doing this be sure to have the line protected by a circuit-breaker or a fuse.

Report the observed relations in the form of curves, and explain them by means of vector diagrams.

VOLTMETER LINE-DROP COMPENSATORS.

463. It is desirable in any system of electrical transmission to be able to read, on a voltmeter placed in the generating station, the actual voltage at the point of consumption of energy. The simplest and the oldest device for this purpose is a pair of *pilot wires* between the point of consumption and the power house. A voltmeter situated in the power station, and connected to these wires, reads the voltage at the farther end of the line, and the generator pressure is regulated accordingly.

As the distance of transmission increases, the cost of pilot wires becomes prohibitive. Devices are used in such cases, that enable the operator in a power house to read the voltage at the receiving end of the line, without pilot wires. Some types of line-drop compensating devices are described below.

464. Direct-Current Compensator. — A simple arrangement of this kind is shown in Fig. 366. The station voltmeter, in addition to its regular winding, has a compensating winding connected in series with the line. This series winding opposes the action of the potential wind-

ing, so that the voltmeter shows less, the heavier the line is loaded. The decrease in reading is proportional to the line current; the drop in the line is also proportional to the line current. Therefore, by suitably adjusting the number of turns on the compensating winding, or by providing a shunt around it, the instrument may be made to indicate the voltage at the receiving end of the line, at any load.

Such a compensating winding may be adapted to almost any commercial type of direct- or alternating-current voltmeter; but the principle is not quite correct on alternating-current lines, because the drop depends in this case not only on the value of the current, but also on the power factor of the load. The arrangement described below takes

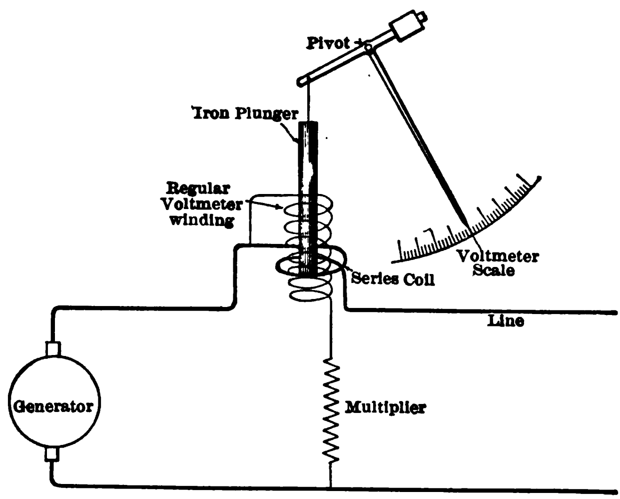


FIG. 366. A voltmeter compensated for line drop, and intended primarily for direct-current circuits.

this factor into account, and is therefore preferable on alternating-current lines.

465. Mershon Alternating-Current Line-Drop Compensator.— The total voltage drop in a transmission line is caused by its resistance and reactance, and is proportional to the current. Therefore, by inserting a certain resistance R and inductance L into the voltmeter circuit (Fig. 367), and making the voltage drop across these proportional to the line current, conditions are created in the *local* circuit, similar to those in the actual transmission line. Consequently, voltmeter readings may be reduced by the amount of the line drop. With this arrangement, the voltmeter, though placed in the power house, automatically reads

the voltage at the receiving end of the line, at any value of the current and of the power factor. V is an ordinary station voltmeter connected to the line through the potential transformer P; if the voltage is sufficiently low, this transformer may be omitted. The resistance R and the inductance L are connected in such a way that the current passing through them is at any moment proportional to and in phase with the line current. This is obtained by the use of two series transformers, C and K, the first of which carries in its primary the whole line current. A part of the circuit R-L is introduced into the voltmeter circuit, as shown in the figure. The points, where the connections are made, are adjustable, so as to be able to compensate for a definite per cent reactive and ohmic drop.

The voltage at the voltmeter terminals is a geometrical sum of the generator voltage, as supplied by the transformer P, and of the voltage

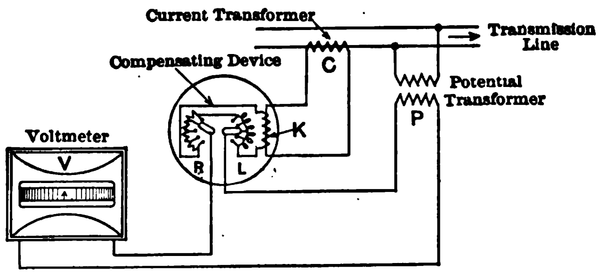


FIG. 367. The Mershon arrangement for compensating a voltmeter for line drop; the method can be used on alternating-current circuits only.

drop across the compensator. The latter voltage is proportional to the line current, and has the same inductive and ohmic components as the actual line drop, provided that the compensator is adjusted correctly. Therefore, the voltmeter shows the generator voltage, less the drop in the line; in other words, the voltage at the receiver end.

The purpose of the series transformer C is to make possible the use of the same compensator on lines having widely different current output. The ratio of turns of this transformer is selected so as to have about 4 amperes in the secondary circuit at full load. The purpose of the transformer K is twofold: it permits of giving the resistance R and the reactance L values most suitable for the voltmeter circuit, and insulates the voltmeter circuit from that of the transformer C. In this way it is possible to use the transformer C not only for the compensator, but also for the ammeter and the series coil of the wattmeter.

466. EXPERIMENT 22-G. — Calibrating Line-Drop Compensators. — (a) Connect a compensated voltmeter to a direct-current line, as shown in Fig. 366. Load the line and calibrate the device by actually reading the voltage at both ends of the line. The adjustment is conveniently made by a shunt around the compensating coil. Adjust the instrument on a heavy load, and see if it reads correctly on partial loads.

(b) Connect the line to an alternating-current supply, and see if the adjustment of the device is still correct with non-inductive loads. If not, adjust it to read correctly; determine per cent error at other values of power factor. After this, take a line having both ohmic and inductive resistances. Adjust the compensator to read correctly at full load and at a power factor of about 80 per cent. Calibrate the instrument within practical values of power factor, say from 50 to 100 per cent, and from half load to load and a quarter.

(c) Connect the compensator shown in Fig. 367 and check its calibration separately for ohmic drop and for inductive drop; then try it on a line having both ohmic and inductive resistances. Compare its indications with voltmeter readings taken at the receiving end of the line, at different values of load and of power factor.

PREDETERMINATION OF REGULATION OF TRANSMISSION LINES.

467. In many cases it is difficult, or even impossible, actually to measure the voltage drop or regulation of a transmission line at its rated load. A method has been devised which permits the calculation of the regulation of a line at any load and power factor, from a simple short-circuit test.

With the same notations as in § 459 the voltage relations at a certain load are represented by Fig. 364. The unknown part of the diagram is the triangle KML, or, with a given current i, the unknown quantities are: the ohmic resistance r and the reactance x of the line. Both may be determined experimentally in the following way: short-circuit the line at the points C and D (Fig. 368) and connect the points A and B to a source of direct current. Read volts and amperes; the ratio will give the ohmic resistance r of the line. Now apply an alternating current, instead of the direct current; again measure the current and the

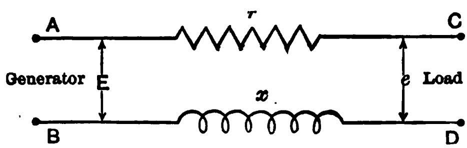


FIG. 368. Determination of impedance of a transmission line from a short-circuit test.

voltage. The ratio will give the impedance of the line. From the data thus obtained, the triangle of drop, shown in Fig. 369, may be constructed, and the reactance x calculated. The values of r and x thus obtained can be used in constructing the diagram, Fig. 364, for any desired values of current and power factor. In practice, simplified methods are employed some of which are described below.

468. Kapp's Diagram.— It is not necessary to construct the diagram, shown in Fig. 364, for each value of power factor or current. The triangle MKL remains the same at any value of the power factor as long as the current remains constant. If the generator voltage OL is constant, the point O travels on a semicircle having L for its center. This gives the so-called Kapp's diagram, shown in Fig. 391; it is the same for transformers, as for transmission lines, and with some limitations is even applicable to alternators.

The triangle MKL is denoted there by OKC; the generator voltage is represented by EC. OI is the direction of the current vector; the receiver voltage is $= EO$. With non-inductive load the receiver voltage is represented by the vector OE_r; at purely inductive load the receiver voltage is OE_x. Should the line draw a leading current, because of its capacity, or of an over-excited synchronous motor, the receiver voltage becomes higher than the generator voltage. The theoretical limit of a pure capacity load corresponds to the vector OE_c. This rise in voltage is explained by a partial resonance between the reactance of the line and the capacity of the load (see § 443).

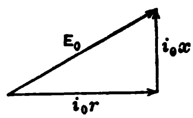


FIG. 369. Triangle of voltages from a short-circuit test.

For other values of the current, the triangle OKC is proportionally reduced in size; the remainder of the diagram is unchanged. If the receiver voltage e, and not the generator voltage E, is maintained constant a semicircle is drawn from the point O as a center. Generator voltages are in this case represented by variable vectors from the point C.

Charts and tables are in existence by means of which voltage drop and regulation can be obtained directly, without constructing a diagram. See articles on the subject in the *Electric Journal,* March and April, 1907; also F. G. Baum's booklet, *Alternating-Current Calculating Device.* Charts will also be found in Foster's *Pocket-Book* and in the *Standard Handbook.*

469. Analytical Calculation of Voltage Drop.—When voltage drop in a line is slight, the difference $E - e$ cannot be obtained with sufficient accuracy from a diagram. It is better in this case to calculate

it analytically. Denoting the angle NOL in Fig. 364 by α we have

$$\begin{cases} E \operatorname{Cos} \alpha = e \operatorname{Cos} \phi + ir; \\ E \operatorname{Sin} \alpha = e \operatorname{Sin} \phi + ix. \end{cases}$$

For a given current i and a phase angle ϕ the angle α may be eliminated from these two equations, and the resultant equation solved for e, or E, whichever is unknown. The solution is simple, when E is unknown; both equations are squared and added together. This gives

$$E^2 = (e \operatorname{Cos} \phi + ir)^2 + (e \operatorname{Sin} \phi + ix)^2 \quad . \quad . \quad . \quad . \quad (5)$$

which is identical with the formula (5) given in § 459. But when e is unknown, the solution becomes more complicated. Reducing eq. (5) to the form of a quadratic equation with respect to the unknown variable e, we have:

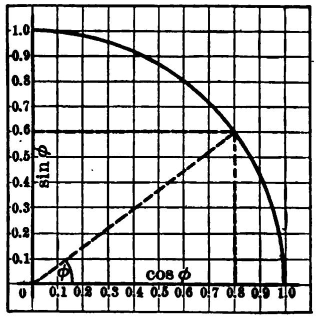


FIG. 370. A diagram giving the values of Sin ϕ and of the angle ϕ for any value of power-factor Cos ϕ.

$$e^2 + 2\, ie\, (r \operatorname{Cos} \phi + x \operatorname{Sin} \phi) - (E^2 - i^2r^2 - i^2x^2) = 0.$$

Solving this equation, gives:

$$e = \sqrt{E^2 - (ir \operatorname{Sin} \phi - ix \operatorname{Cos} \phi)^2} - (ir \operatorname{Cos} \phi + ix \operatorname{Sin} \phi) \quad . \quad . \quad . \quad (6)$$

When the line drop is comparatively small, the second term under the radical sign can be neglected, as compared to E, and we have

$$e \text{ (approx.)} = E - (ir \operatorname{Cos} \phi + ix \operatorname{Sin} \phi). \quad (7)$$

Let, for instance, the ohmic drop ir be 5 per cent of E, the inductive drop $ix = 7$ per cent of E; let it be required to determine the receiver voltage and per cent line drop when the power factor of the load is 80 per cent lagging. We have from trigonometric tables, or from Fig. 370, that, when Cos $\phi = .80$, Sin $\phi = .60$. Consequently, the approximate formula (7) gives:

$$E - e = (.05 \times .80 + .07 \times .60) E = .082\, E,$$

so that the arithmetical difference between the generator voltage E and the receiver voltage e is $= 8.2$ per cent of E. Applying the exact formula (6), gives the line drop equal to $.086\, E$, or 8.6 per cent of the generator voltage.

470. EXPERIMENT 22-H. — Predetermination of Regulation of a Transmission Line. — The method is explained in § 467. Short-circuit the terminals at one end of an experimental line containing

some ohmic and inductive resistance (Fig. 363). Send a direct current through the line, gradually increasing it to the safe limit: read volts and amperes. Repeat the same experiment with alternating current. This comprises all the necessary experimental data.

In order to have a check on the predetermined regulation, it is well to take a few readings with the line actually loaded, preferably with considerable currents, in order to have a large drop. Take a curve of voltage drop, at a current corresponding to 50 per cent overload, between as wide limits of power factor as possible.

Report. From the short-circuit test figure out the resistance and the reactance of the line (Fig. 369). Construct Kapp's diagram for a current for which the regulation was determined experimentally; check a few calculated voltages with those taken experimentally. Figure out a few points by using the charts mentioned at the end of § 468, and the formulæ deduced in § 469. See how closely Kapp's diagram checks with them.

CHAPTER XXIII.

DISTRIBUTING LINES.

471. As is explained in Art. 446, the principal distinction between a distributing line and a transmission line is that the latter is loaded at the end only, while a distributing line has power led off at different points (Fig. 371). Only one side of the line (say positive) is shown in

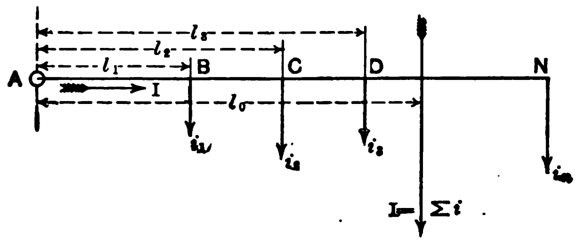


FIG. 371. A distributing line fed from one end.

this and in the following two sketches; the relations in the negative, or the return wire are exactly the same.

The principal types of distributing lines met with in practice are:

(1) Lines fed from one end (Fig. 371).

(2) Lines fed from both ends (Fig. 372).

(3) Ring lines (Fig. 373).

A ring-conductor is evidently but a special case of a line fed from two

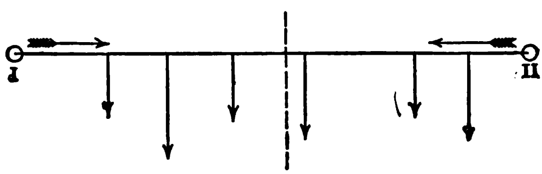


FIG. 372. A distributing line fed from both ends.

ends. City networks are usually laid out so that street conductors are fed, if possible, from at least two points, as shown in Fig. 372. In case of an accident to one of the feeders the customers may still be

temporarily supplied from the other feeder, even though the service be not as satisfactory, because of a greater voltage drop.

472. Voltage Drop with Distributed Load. — The voltage drop in a line fed from one end (Fig. 371) may be calculated on the basis of formula (1) given in § 447. With the same notation as there we have for the drop to the farthest consumer N,

$$\frac{pe}{100} = \frac{I.\rho.2\,l_1}{q} + \frac{(I - i_1).\rho.2\,(l_2 - l_1)}{q} + \frac{(I - i_1 - i_2).\rho.2\,(l_3 - l_2)}{q} + \ldots\ldots$$

The first term on the right side of this equation represents the voltage drop across AB, the second across BC, etc. In this formula i_1, i_2, i_3, etc., represent the currents taken by various consumers; the current

$$I = i_1 + i_2 + i_3 + \cdots\cdots$$

is the total current supplied from the feeder. After simple mathematical transformations the above formula is reduced to

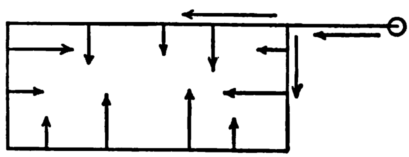


FIG. 373. A ring line.

$$\frac{pe}{100} = \frac{2\,\rho}{q}\,(i_1l_1 + i_2l_2 + i_3l_3 + \cdots)$$

or finally to

$$pq = \frac{200\,\rho\,\Sigma il}{e} \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

This formula is perfectly analogous to the expression (1) given in § 447; it is used for determining the cross-section of a conductor when the load is given; or for determining the load that a given conductor can carry under the condition that the voltage drop should not exceed a certain limit.

The expression (5) shows that the voltage drop in a conductor loaded at several places depends not only on amperes load but on *the position of the load* as well. A small load situated far from the feeder A may affect the line drop quite as much as a comparatively heavy current taken near the feeder. In other words, *voltage drop with distributed load is proportional not to amperes, but to ampere-feet.*

It used to be customary to measure load by the number of 16-candle-power lamps instead of by amperes. To show the application of formula (5), suppose that it is required to figure the sizes of street conductors in a city, the maximum drop allowed being 2 per cent, and

the pressure 100 volts. For copper conductors ρ = about 10 ohms; a 100-volt 16 candle-power lamp consumes about 0.5 ampere, and we have

$$q = \frac{200 \times 10 \times 0.5 \Sigma Ll}{100 \,.\, 2},$$

or

$$q = 5 \Sigma Ll,$$

where number of lamps L is introduced instead of amperes i. Knowing the number of lamps to be connected at different places along a certain conductor, its cross-section in circular mils can be easily found from this formula.

The expression Σil may be represented in the form $Il_0 = l_0 \Sigma i$, where l_0 is the distance from A to the "center of gravity" of the load (Fig. 371), considering i_1, i_2, i_3, etc., as if they were mechanical forces, applied at the distances l_1, l_2, l_3, etc.; I is the total load of the line. With this substitution, formula (5) becomes:

$$pq = \frac{200 \rho . Il_0}{e} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

473. Experimental Lines. — Experimental lines for studying voltage and current relations with distributed load are preferably made of German silver, manganin, or any other material of a comparatively high specific resistance, and a low temperature coefficient. Incandescent lamps of 4, 8, 16, and 32 candle-power may be conveniently used as a load. It is simpler and preferable to have only one side of the line made of high-resistance material, the return wire being replaced by a heavy copper wire or a bar of a negligible resistance, as in Fig. 353.

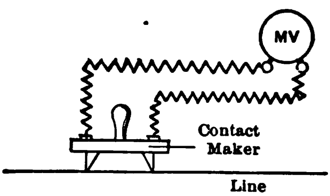


FIG. 374. A contact-maker for measuring currents in a wire.

It would not be feasible to have ammeters or even ammeter shunts connected in different places of the line, as this would change the uniform resistance of the line per unit length. It is better to use parts of the line itself as ammeter shunts, the drop being taken by a contact-maker, shown in Fig. 374. The milli-voltmeter MV, connected to the knife-edges of the contact-maker, measures a voltage drop which is proportional to the line current, and thus, if the proper constant be applied, measures the current itself. The distance between the contacts may be made adjustable, so as to give this constant a simple value.

Two voltmeters should be used, one for keeping the terminal voltage constant, another with a three-volt scale for measuring the voltage

drop along the line. One double-scale voltmeter may be substituted for the two instruments, and a double-throw switch provided for using either scale. The return wire of the experimental line should be made inaccessible, so that the student could not, by mistake, touch it with one of the voltmeter leads connected to the three-volt scale.

474. EXPERIMENT 23-A. — Voltage Drop in Distributing Lines Fed from One End. — The arrangement of an experimental line is described in § 473; the formula for drop is given in § 472. (1) Connect to the line a certain distributed load, as in Fig. 371, and trace out the voltage drop along the line with the three-volt voltmeter. Using the contact-maker, measure the currents taken by separate consumers; as a check measure the currents in various parts of the line itself. Repeat the same experiment with a different distribution of load. (2) Connect

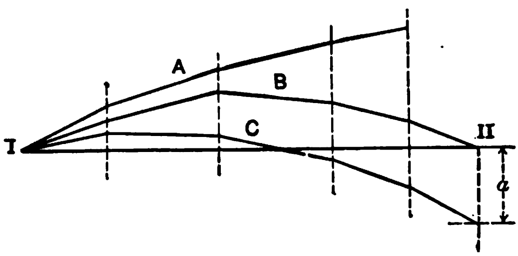


FIG. 375. Voltage drop in lines fed from one end and from both ends.

to the line a consumer near the source of power, and another one as far from it as possible. Measure the voltage which both of these consumers get, as other lamps are gradually connected to the line. This should illustrate the fact that the consumer at the end of the line is affected by a fluctuating load much more than the consumer at the beginning of the line. (3) Investigate the influence of the factor $\Sigma\, il$ on voltage drop to the consumer at the end of the line. Connect to the line a certain number of lamps near the feeding end, and then the same number of lamps near the opposite end of the line. Measure, in both cases, the voltage at the terminals of the last consumer. It will be found that the same number of lamps affect his voltage differently in the two cases. Now change the number of lamps in one of the groups until he gets the same drop in both cases. Verify, that in this case the number of ampere-feet ($\Sigma\, il$) is the same in both groups of lamps. (4) Before leaving the laboratory, measure the resistance of the line wire per foot of its length, using the drop-of-potential method. Make a sketch of the line with distances between the connections to the consumers; measure the distance between the knife-edges of the contact-maker.

Report. Plot to conductor lengths as abscissæ voltage drop as shown by the curve A in Fig. 375. I is the feeding-point corresponding to the point A in Fig. 371; the dotted lines indicate the places of connections to the customers. Check the observed results by calculating the drop from the known values of the line resistance and the currents. Give and explain the results showing that voltage fluctuations are most pronounced at the consumers remote from the feeding-point. Show from the observed data that the voltage drop is the same with different distribution of the load, as long as Σil has the same value.

475. Line Fed from Both Ends. — When a conductor is fed from two ends (Figs. 372 and 373) there is always a point of division, on one side of which the customers are supplied with current from one feeder, on the other side from the other feeder. The position of this point depends on the instantaneous load, and is always such that Σil is the same on each side of the point of division. This follows immediately from formula (5), because the conductor may be cut in two at the point of division of the load, and each half considered as a line fed from one end. The condition must then be fulfilled that the drop from both feeding points is the same; the drop being proportional to the value of Σil, we have

$$(\Sigma il)_{\mathrm{I}} = (\Sigma il)_{\mathrm{II}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

In figuring out the cross-section of a line fed from two ends, all the consumers are supposed to be connected simultaneously, and the point of division determined under these most unfavorable conditions. Then the conductor is assumed cut in two at this point and the cross-section figured out from formula (5).

In some cases the pressure is different at the two feeding-points, because the feeders themselves may have different cross-sections, different lengths, and carry different loads. In such cases, the feeder with a higher voltage carries a proportionately larger part of the load. The above rule, that the point of division of the load is determined by the expression (7), is only true when the same voltage is maintained at I and II. If the voltage at II is a per cent higher, we have, according to the formula (5),

$$p = \frac{200\,\rho\,(\Sigma il)_{\mathrm{I}}}{qe},$$

and

$$a + p = \frac{200\,\rho\,(\Sigma il)_{\mathrm{II}}}{qe}.$$

Subtracting one equation from the other we get

$$a = \frac{200\,\rho}{qe}[(\Sigma il)_{\mathrm{I}} - (\Sigma il)_{\mathrm{II}}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

When $a = 0$, this is reduced to the former condition $(\Sigma il)_{\mathrm{I}} = (\Sigma il)_{\mathrm{II}}$. Formula (8) determines the position of the point of division of the load, with a given difference of potential a per cent between the feeders. By inserting some resistance in one of the feeders, part of its load can be transferred to the other feeder, and vice versa.

The ring-line, Fig. 373, is evidently identical, from an electrical standpoint, with a line fed at the same potential from both ends.

476. EXPERIMENT 23-B. — Voltage Drop in Distributing Lines Fed from Both Ends. — The arrangement is similar to that used in Experiment 23-A, except that feeders are connected from the source of supply to both ends of the line, and rheostats are provided for regulating each feeder independently.

(1) Load the line, and take the distribution of voltage drop with only one feeder connected to it (Curve A, Fig. 375). (2) Connect the other feeder and see in how far the conditions are improved, and what part of the load is taken by the second feeder (Curve B). Keep both feeders at the same potential and determine the point of division of the load. Measure volts and amperes at separate consumers, in order to be able to check the results by calculation. (3) Raise the potential of one of the feeders slightly, and find the new distribution of currents and voltages; also the new point of division of the load (Curve C). (4) Repeat the same experiment with a larger difference of potential at the two feeders. (5) Before leaving the laboratory, measure the resistance of the line wire per foot of its length, using the drop-of-potential method. Make a sketch of the line, with distances between the connections to the customers; measure the distance between the knife-edges of the contact-maker.

Report. (1) Plot to conductor lengths as abscissæ, voltage drop as shown in Fig. 375. Curve A refers to a conductor fed from one end, B — fed from both ends at the same voltage, and C — when the feeder at II has a voltage a per cent higher than that at I. (2) Check the observed drop by calculation, from the resistances and currents. (3) Show that the point of division of the load, as found during the experiment, satisfies the condition expressed by formula (7), when the two feeding-points are at the same potential, and that its position is in accordance with formula (8), when the potential is different.

INSULATION MEASUREMENTS AND LOCATION OF FAULTS.*

477. All parts of an electric circuit must be either thoroughly insulated from the ground or carefully grounded. The return wire of a trolley circuit and the middle wire of a three-wire system are examples of grounded parts of the circuit; most other parts have to be thoroughly insulated from the ground. One accidental ground connection may not be objectionable, at least on low-voltage circuits, unless there is a regularly grounded wire; in this latter case a second ground means a short circuit.

However; since even one ground connection means that the insulation is becoming defective, action should be taken before the fault

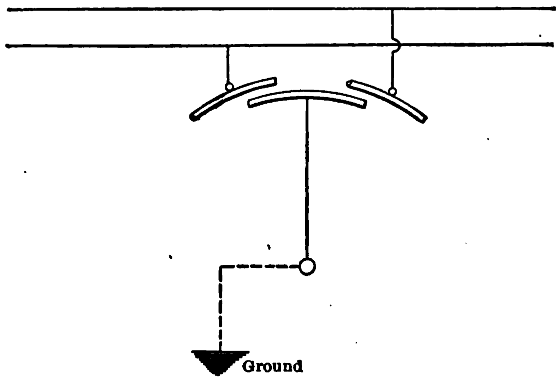


FIG. 376. A static ground-detector.

has assumed such proportions as to make necessary the shutting down of the station, or at least cutting out the damaged part of the circuit. Any apparatus which indicates a ground connection, or defective insulation, is called a *ground detector*. On high-tension circuits static ground detectors are used (Figs. 376 and 377); on low-tension circuits ordinary incandescent lamps or a voltmeter are preferable (Fig. 378), since the static instrument in its usual form requires a considerable voltage in order to give a noticeable deflection.

478. Static Ground Detectors. — The ground detector, shown in Fig. 376, consists of two stationary metal pieces connected to the wires of the circuit, and of a movable vane connected to the ground. As long as the line is perfectly insulated from the ground, the vane remains in

* The methods described below apply equally well to transmission lines and to distributing lines.

its middle position, equal static charges being induced on both sides. When one of the line wires becomes grounded, it can induce no more charge, the vane itself being connected to the ground; therefore the vane is attracted toward the other side, and the deflection is shown on the scale. A ground does not necessarily mean a direct metallic connection to the ground; it may be merely a leak through the insulation, having a resistance of several thousand ohms. The deflection of the pointer depends on this "resistance to the ground," and the scale

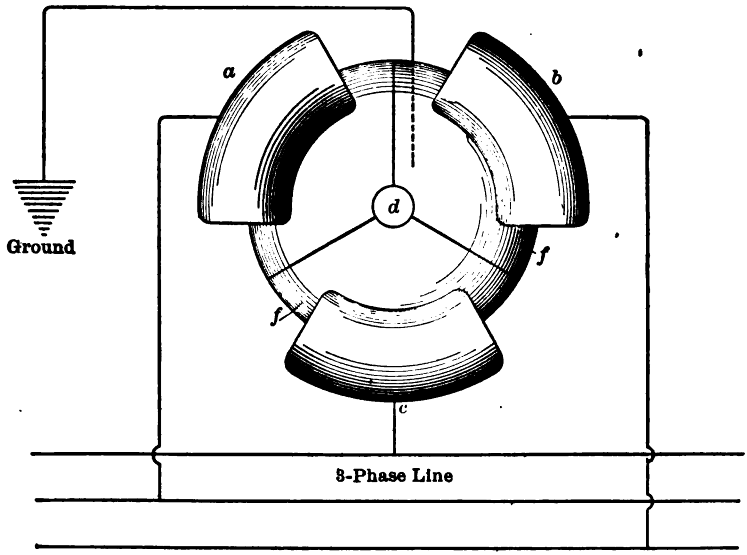


FIG. 377. A three-phase ground-detector.

of the instrument may be calibrated in ohms, or any other arbitrary units.

On three-phase circuits a ground detector is used, shown in Fig. 377; it operates on the same principle as the one described above, but has three stationary parts, instead of two, according to the number of line wires. The movable part is pivoted so that it can move in all directions around a point. As in the single-phase ground detector, the vane moves *from* the grounded wire.

479. Ground-Detector Lamps and Voltmeters. — The low-tension ground detector, shown on the left of Fig. 378, consists of ordinary incandescent lamps connected across the line; the middle point is thoroughly grounded. A sufficient number of lamps is taken so that they just glow red when there is no ground. Should a dead

ground occur on one of the wires, one half of the lamps go out, while the other half glow bright. Any fault on one side of the line is shown by the lamps on the other side glowing brighter. This arrangement is very simple and reliable, but does not allow of any quantitative determination of the resistance of the fault. This is remedied by the addition of a voltmeter, as shown in the same sketch to the right. Knowing the resistance of the instrument, the resistance to the ground can be calculated from the voltmeter indication. Or else, the voltmeter can be calibrated directly in ohms, instead of volts.

480. EXPERIMENT 23-C. — Calibration of Ground Detectors. — The experiment consists of a study of ground-detecting devices described in §§ 478 and 479. The following separate measurements should be performed:

(1) Connect ground-detector lamps, as in Fig. 378, and observe their action when one of the line wires has a fault or a dead ground. Calibrate the lamps qualitatively, so as to be able to judge regarding the magnitude of a fault. For instance, when the insulation resistance of a fault is about 2500 ohms, the difference in brightness of the two lamps is just noticeable in a rather dark place. The difference in brightness is easily detected at 1500 ohms; one lamp apparently goes out at 200 ohms, etc. Investigate the influence of the number of lamps in series on sensitiveness of the indications.

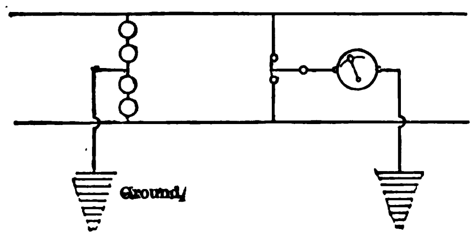


FIG. 378. Ground-detecting lamps and voltmeter.

(2) Calibrate an ordinary voltmeter (Fig. 378) for ohms leakage resistance to the ground. This should be done on a low-voltage circuit (not more than 500 volts). Connect the voltmeter across the line and gradually increase the resistance in series with it by means of a calibrated multiplier. The calibration curve is that between the deflections and the resistances in the multiplier. No actual ground is used in calibration, but the electrical conditions are the same as in Fig. 378.

(3) Calibrate a static ground detector (Fig. 376) for ohms resistance to the ground. The necessary voltage, say 2200 volts, may be obtained by an ordinary voltmeter transformer. For calibration use high-resistance carbon rods, the resistance of which has been previously determined by some other method, — for instance, by the Wheatstone bridge. Connect the stationary blades of the ground detector to the

line, and place the carbon rods between one of the line wires and the moving element. The observed deflections, plotted to resistances of the rods, constitute the calibration curve of the ground detector. Here again, no actual ground need be used in the calibration; however, the electrical connections are identical with those obtaining when a fault exists on one of the line wires, and the moving element is connected to the ground.

481. Insulation Measurements on Dead Lines. — Insulation measurements may be conveniently performed, if the line can be disconnected from the source of power during the test. A separate source of power should be used in this case, the voltage of which must be at least as high as that to which the line is subjected in regular operation.

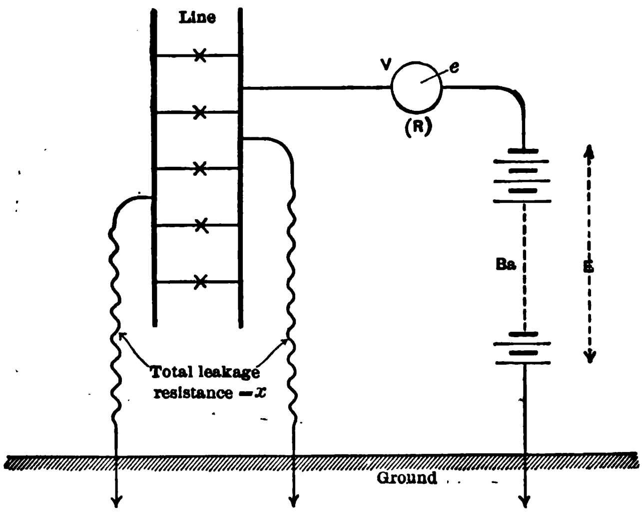


FIG. 379. Measuring insulation of "dead" lines.

Sometimes the regular source of power, to which the line is later connected, is used for tests. The connections for insulation measurements are shown in Fig. 379: a voltmeter of a known resistance R is connected first across the source of voltage Ba, and then between the source and the line, as shown in the sketch. Let the first reading be E, the second e. Then, if the resistance of the fault is x we have,

$$\frac{R + x}{R} = \frac{E}{e},$$

whence

$$x = R\frac{E - e}{e} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The voltmeter in both cases measures the voltage of the source of power, save that in the first case it is connected to it directly, in the second case through the unknown resistance x of the fault, which thus acts as a multiplier. The deflections of the voltmeter are inversely proportional to the total resistance in the voltmeter circuit. This gives the above equation, from which the resistance to the ground may be calculated. For values of insulation resistance, prescribed by the Fire Underwriters for complete installations, see section 66 of the "National Electrical Code."

482. Evershed Ohmmeter. — There are instruments on the market which give the resistance of a fault directly in ohms, and supply their

FIG. 380. The Evershed ohmmeter.

own source of power. A popular instrument of this kind is the Evershed ohmmeter, shown in Fig. 380. The box to the right contains a small D. C. generator which is operated by hand through a gearing. The generator may be wound for any voltage up to 1000 volts. The box to the left contains a special galvanometer with a scale calibrated in megohms. The connections shown in the sketch are those for measuring the insulation between two cables. If the insulation is to be measured between a cable and the ground, one of the terminals to the left is connected to the cable conductor, the other to its lead sheathing.

The construction of the galvanometer is shown in Fig. 381. The moving part consists of a soft-iron needle n with a pointer attached to it. The coils cc are connected in series with the generator circuit, the coil pp across the unknown resistance X. The magnetizing action of

the coils *cc* tends to set the needle in the position corresponding to zero of the scale. The action of the coil *pp* tends to set the needle in the position of "infinite resistance." When currents flow through all the coils, the needle assumes an intermediate position which depends on the ratio of the magnetizing actions of *pp* and *cc*. But the current in *pp* is proportional to the pressure at the terminals of the unknown resistance; the current in *cc* is equal to that flowing through the unknown resistance. Therefore, the ratio of the actions of the two coils is a measure of the unknown resistance (voltage ÷ current).

The scale is calibrated empirically by known resistances. The proper speed of rotation for the generator handle is about 60 revolutions per

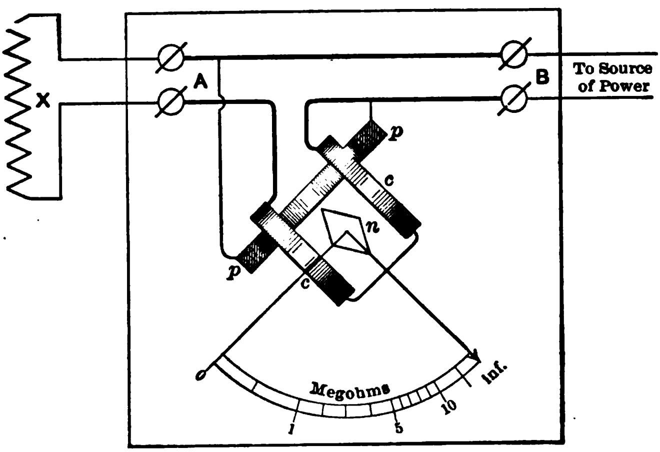


FIG. 381. The operating parts of the Evershed ohmmeter.

minute. The needle is made astatic, so that the indications of the instrument are independent of the direction of the test current and of terrestrial magnetism.

The Sage ohmmeter, described in § 19, and the portable bridge, shown in Figs. 23 and 24, may also be used for measuring insulation resistances of lines. It must be kept in mind, however, that these devices use low-voltage batteries; in some cases a fault does not show up unless a sufficiently high voltage is applied. Therefore, the voltmeter method (§ 481) is preferable, unless an ohmmeter like Evershed's is available, with which comparatively high voltages may be used.

483. Insulation Measurements on Live Lines. — On low-voltage lines accurate determinations of insulation resistance are possible even when the line is in use. The principle of the method is the same as

in the ground-detector voltmeter (Fig. 378). The relations are shown more in detail in Fig. 382. A voltmeter of a known resistance R, shows a voltage e_p when connected between the positive wire and the ground; it shows e_n between the negative wire and the ground. The unknown insulation resistances between the line wires and the ground are denoted by x_p and x_n .

Assume first that a fault exists on the positive side only. Then x_n =

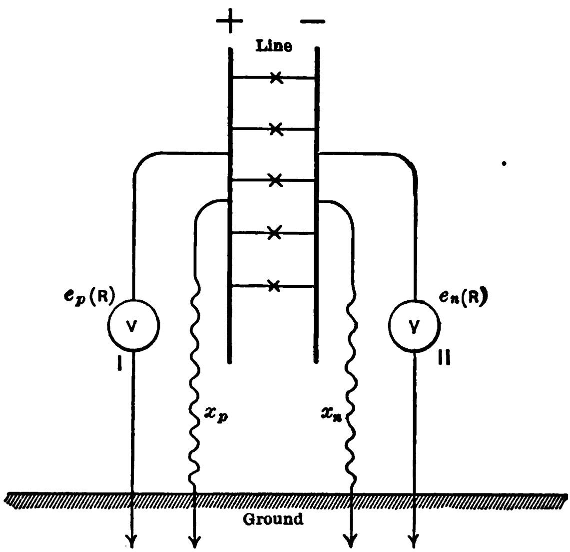


Fig. 382. Insulation measurements on "live" lines.

infinity, and $e_p = 0$. If the voltmeter reads a voltage E across the line, we have the same relation as in § 290:

$$x_p = R\frac{E - e_n}{e_n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The path of the leakage current is from the positive side of the line, through the fault x_p, the ground and the voltmeter e_n to the negative side of the line.

The relations become more complicated when the insulation is defective on both sides, so that the voltmeter gives appreciable deflections in position I and in position II. When the voltmeter is connected between the positive wire and the ground, the leakage current flows through x_p and the voltmeter in parallel with it, through the

ground and back through x_n to the negative line wire. The total resistance of the leakage circuit is thus

$$\frac{Rx_p}{R + x_p} + x_n,$$

and the leakage current

$$i = \frac{E}{\dfrac{Rx_p}{R + x_p} + x_n}.$$

The part of this current which flows through the voltmeter is calculated as follows: The currents in parallel are inversely as the resistances of the paths; hence, $i'R = (i - i')\, x_p$, where i' is the current through the voltmeter, and $(i - i')$ is the current in x_p. Solving the last equation for i' gives

$$i' = ix_p \div (R + x_p).$$

On the other hand,

$$i' = e_p \div R,$$

because the voltmeter reading is e_p and the resistance of the instrument is R. Eliminating i and i' from the preceding equations, we get

$$\frac{e_p}{Rx_p} = \frac{E}{x_nR + x_nx_p + x_pR} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

When the voltmeter is connected between the negative wire and the ground, we get by analogy

$$\frac{e_n}{Rx_n} = \frac{E}{x_pR + x_px_n + x_nR} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

or, from the last two equations, the simple result

$$\frac{e_p}{x_p} = \frac{e_n}{x_n}.$$

Eliminating x_n by means of this equation from (11), we finally obtain

$$x_p = R\,\frac{E - e_n - e_p}{e_n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and by analogy

$$x_n = R\,\frac{E - e_n - e_p}{e_p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Using these expressions, the unknown resistances to the ground are calculated from the voltmeter readings e_p and e_n. If the voltmeter shows 0 on the positive side, equation (13) is reduced to (10). Equation (14) shows that in this case there is no fault on the negative side (x_n = infin.).

484. EXPERIMENT 23-D. — Insulation Measurements on Low-Tension Lines. — The methods are described in §§ 481 to 483. (1) Measure the insulation of a dead line by the method shown in Fig. 379. Connect the line to a gas- or water-pipe through a resistance box, and take voltmeter readings with the value of this resistance varied from zero to infinity. Determine the resistance of the voltmeter by taking a reading of some constant voltage without multiplier, and with a multiplier of known resistance. The insulation of the line under test may not be quite perfect; therefore it is better to use an *artificial* ground, for instance, a wire carefully insulated from the earth. The leakage to this artificial ground may be made to be of any desired value.

(2) If a direct-reading ohmmeter is available, calibrate it with standard resistances; then use the instrument for determining the insulation resistance of actual lines previously disconnected from the supply. Perform this test in accordance with section 66 of the *National Electrical Code.*

(3) Measure insulation resistance of a live line, as explained in § 483. As the line available for test may have a fault to the ground, use an artificial ground, so as to establish known values of leakage resistances x_p and x_n (Fig. 382), by means of calibrated resistance boxes. Apply the method to the actual measurement of the insulation between the line and the earth, without resistance boxes. Before leaving the laboratory, measure the resistance R of the voltmeter.

Report. Give the results of the test (1) and show how nearly the resistances calculated from formula (9) check with those actually used in the resistance box. Give the results of practice with the direct-reading ohmmeter. Calculate the insulation resistances from the test (3) and compare them with those actually connected between the line and the ground.

485. Locating Faults. — After a fault has been discovered by a ground detector, by measuring insulation resistance, or by some disturbance in the operation of the line, the next problem is to locate the fault, in order to remedy it. Two schemes for locating faults on long lines are widely used in practice, both being based on the familiar principle of the Wheatstone bridge. The method shown in Fig. 383 is called the Murray loop (§ 486); it is convenient for use with a slide-wire Wheatstone bridge, such as is shown in Fig. 12. With plug or dial-type bridges (Figs. 21 and 22), the Varley loop (§ 487), shown in Fig. 384, is preferable. With both methods the two ground connections d_1 and d_2 are in the battery circuit, outside the bridge proper, so that the resistance of the fault, even though considerable, does not affect the result.

Portable bridges, such as are shown in Figs. 15 and 23 (Vol. I), and are intended for general commercial work, usually have a provision for the connections according to the Murray or Varley loop. Explicit instructions for such tests always accompany the bridge.

The place of a cross of one wire on another may be determined in the same way as a fault to the ground, the good wire being considered as an artificial ground.

486. Murray Loop. — The line is short-circuited on one end and connected to a slide-wire Wheatstone bridge on the other end, as shown in Fig. 383. The connections and the lettering are identical with those of a regular Wheatstone bridge (Fig. 10); the battery circuit is closed through the ground. The ratio of the lengths *m* to *n* on the slide-wire of the bridge gives directly the ratio of the distances to the fault

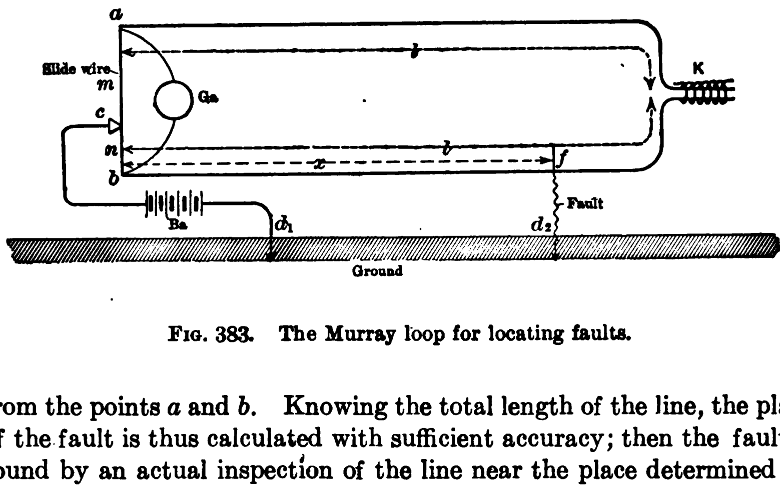


FIG. 383. The Murray loop for locating faults.

from the points *a* and *b*. Knowing the total length of the line, the place of the fault is thus calculated with sufficient accuracy; then the fault is found by an actual inspection of the line near the place determined by calculation.

With the notations in the sketch, we have, when zero balance of the galvanometer is obtained,

$$\frac{2l - x}{x} = \frac{m}{n}$$

or

$$x = l \cdot \frac{2n}{m + n}.$$

487. Varley Loop. — Instead of varying the ratio $m \div n$ for obtaining the galvanometer balance, as is done in the Murray loop, here this

ratio is left constant; but some resistance r (Fig. 384) is gradually added to the line, until the galvanometer shows zero. Then with the notations in the sketch we have

$$\frac{(2l - x)a}{r + xa} = \frac{m}{n},$$

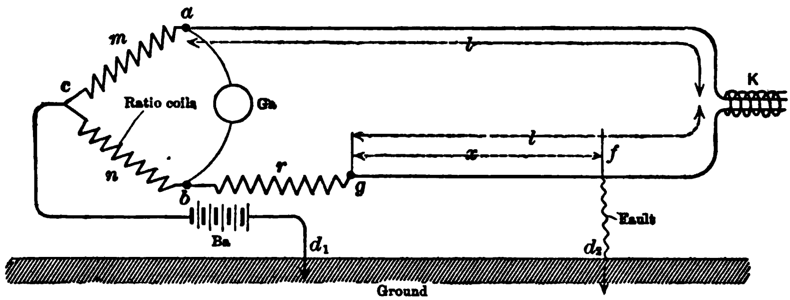


FIG. 384. The Varley loop for locating faults.

where a is the resistance of the line conductor per unit length. Solving this equation for the distance x to the fault, we get

$$x = 2l \cdot \frac{n}{m+n} - \frac{r}{a} \cdot \frac{m}{m+n}.$$

All the quantities in this formula are known, and x may be calculated.

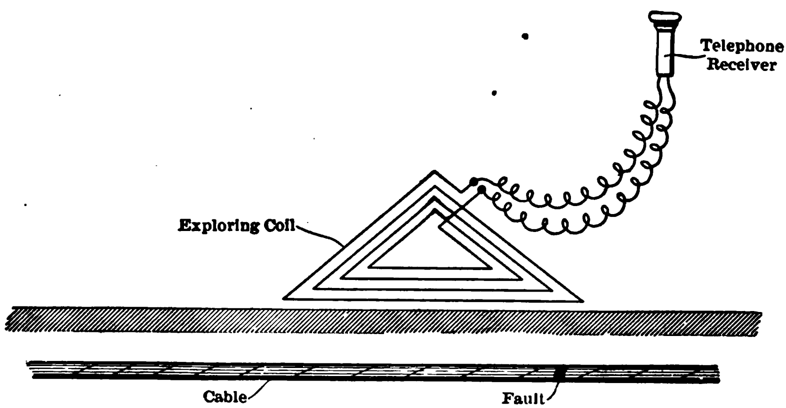


FIG. 385. An induction fault-localizer.

If a is not known, the bridge is connected to the line in the ordinary

way, and the resistance of the total loop measured. Dividing it by the length $2\ l$ gives the resistance a per unit length. When $r = 0$, the above expression becomes identical with that deduced for the Murray method.

For arrangements used in localizing faults on three-wire systems, see an article in the *Electrical Review*, London, March 15, 1907.

488. Induction Localizers. — The devices shown in Figs. 385 and 386 are used to some extent for localizing faults in cables, using alternating current. Either a telephone receiver or an alternating-current ammeter may be used as an indicator.

With the device shown in Fig. 385, alternating current is put on the defective cable, or between the cable and the ground, as the case may be, and the observer listens to the noise produced in the telephone receiver by secondary currents induced in the triangular coil. He follows the cable, and when he passes the fault, the noise either increases or decreases; this change in noise locates the fault.

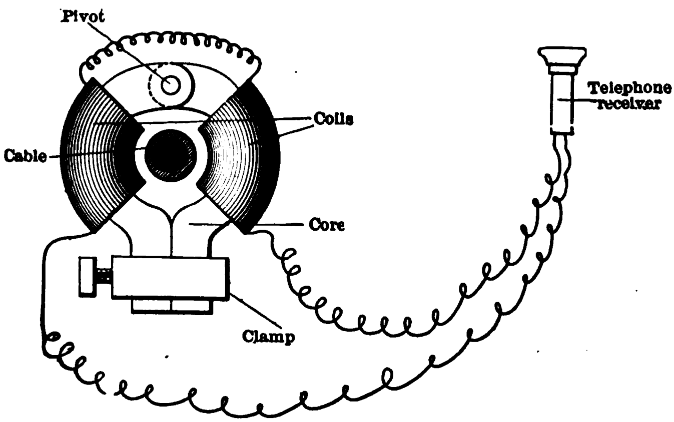


FIG. 386. A fault-localizing transformer.

The device shown in Fig. 386 is a series transformer for which the faulty cable serves as a primary; the secondary is connected to an ammeter, or to a telephone receiver. The core of the transformer consists of two parts hinged together, so that the device can be put on the cable at any place. The position of the fault is indicated by a change in the hum produced in the telephone receiver, or by a change in the ammeter current. The same device may be used for measuring currents in cables, without opening the circuit.

489. EXPERIMENT 23-E. — Locating Faults in Lines. — The experiment is intended to afford practice with the devices and methods described in §§ 485 to 488. At first, the student himself should provide faults on the lines given him, and check the position of the fault by observation and calculation. Then he should try to locate faults, provided for him by the instructor, and hidden so that they could not be located by a mere inspection of the line.

NOTE. The above described methods for locating faults are not always applicable on high-tension transmission lines, since a high voltage is often required to produce a flow of current through a partially disabled insulator. A method for quickly locating such grounds, using the line voltage, has been described by Mr. L. C. Nicholson, in a paper entitled *Location of Broken Insulators*, read before the Annual Convention of the American Institute of Electrical Engineers, in June, 1907. The method is being successfully used on some 60,000 volt lines radiating from Niagara Falls.

CHAPTER XXIV.

THE TRANSFORMER — COMMERCIAL TESTS.

490. Transformers are usually tested for:

(a) *Efficiency;*

(b) *Temperature rise* in continuous operation;

(c) *Voltage regulation,* determined by the voltage drop inside the transformer itself.

(d) *Dielectric strength of insulation.*

Efficiency tests and calculations are given in §§ 315 and 316 of the first volume. The methods of testing transformers for the other three requirements are described below.

TEMPERATURE RISE.

491. Safety of operation of a transformer depends essentially on the maximum temperature which it attains under load. An insulation which can stand a considerable over-potential at ordinary temperatures, easily breaks down when subjected to a sufficiently high temperature. Transformer iron undergoes so-called "aging" under the influence of heat, its properties being changed so that the hysteresis loss increases considerably. This in turn increases the temperature of the transformer. Therefore a test for temperature rise under actual load conditions is one of the most important practical transformer tests.

"In electrical conductors, the rise of temperature should be determined by their increase of resistance, where practicable. Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers. In very low resistance circuits, thermometer measurements are frequently more reliable than measurements by resistance method. Where a thermometer, applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted." (Sec. 266 of the Standardization Rules of the American Institute of Electrical Engineers.)

A transformer heats up in operation because of its core loss and of the I^2R loss in its windings. Core loss depends on the flux in the iron, or, which is the same, on the applied voltage, and is practically independent of the load; copper loss is directly proportional to the square of

the current flowing through the windings. Therefore, in order to determine temperature rise in a transformer, it must be subjected to its full rated voltage and full-load current simultaneously.

Such a test offers no difficulties with small lighting transformers, which can be loaded on lamp rheostats, etc.; but with large high-tension transformers a load test is not only difficult and expensive but in many cases impossible. When two similar transformers are available one transformer can be loaded on the other, and this latter connected back to the source of supply, so that no power is wasted except that necessary for supplying the losses in both transformers. This so-called "pumping-back" method, also known as the "stray power" or "opposition" method, is used in testing not only transformers but generators and motors as well (Chaps. XIV and XXVII).

492. Opposition Test on Transformers. — The connections for an opposition heat test on two transformers are shown in Fig. 387. A and B are the two transformers under test; their low-tension windings are connected in parallel to the power supply, and the high-tension windings are connected *in opposition to* each other. As the transformers are identical, no current flows through their secondaries, and but a small magnetizing current flows through the low-tension windings. At the same time full iron loss takes place in the cores of the transformers, they being subjected to the full rated voltage. If now a full-load current should be made to circulate in the windings, the transformers would be under the same conditions of heating, as under actual full load. As we are here concerned with I^2R loss only, it is not necessary that the heating current should be an alternating current of the right frequency; it may be a current of any frequency, or even a direct current. If no suitable alternating current is available, both the high- and the low-tension circuits can be opened at some place, and sources of direct current introduced, sufficient to produce the desired currents in the windings.

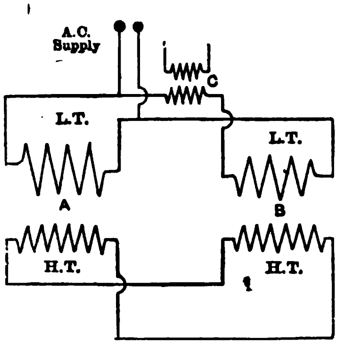


FIG. 387. Heat run on two transformers connected in opposition.

A more convenient method is to open but one of the circuits, say the primary, and to introduce there a comparatively low-voltage source of alternating current of any frequency. This auxiliary source is shown in figure in the form of a transformer C. By regulating the voltage of this source, a full-load current can be produced in the primaries

of the transformers under test; this current induces in turn a full-load current in the secondaries, which therefore need not be opened for any purpose. This is particularly convenient when the secondaries are wound for comparatively high voltages.

In this test the transformers are under actual load conditions as far as the losses and heating are concerned; at the same time, the energy supplied from outside is merely sufficient to cover the losses. For instance, with two 1000-kw. transformers having a full-load efficiency of about 98 per cent, the total expenditure of power with the above test would be but 40 kw.

When but one transformer is available, the same test may be performed by connecting in opposition the two halves of both windings.

493. Extrapolation of Heating Curves. — Commercial transformers usually attain their final temperature after a full-load run of 10 hours or thereabouts; therefore it is out of the question to attain this final state during a laboratory exercise. The following method makes it possible *to predict* the final temperature, and also to figure out approximately the maximum load which the transformer under test can carry continually.

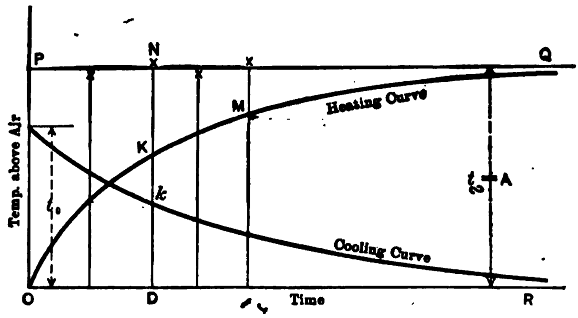


FIG. 388. Analysis of heating and cooling curves.

Let OMQ (Fig. 388) be the "heating" curve of a transformer, or the curve of temperature rise with time. Assume that only the part OM could be determined experimentally, and that it is required to find the position of the line PQ of the ultimate temperature rise, also to construct a portion of the curve beyond M. The method for doing this is given below without proof; for a mathematical proof of the formulæ used, the reader is referred to §§ 496 and 497.

Let abscissæ of the heating curve, representing time, be denoted by x, and ordinates, or temperature rise above air, by T. Let the abscissa and the ordinate of the point M be x_4 and T_4. Divide x_4 into four equal parts corresponding to the points with abscissæ:

$$\left.\begin{aligned} x_1 &= x_1 \\ x_2 &= 2\,x_1 \\ x_3 &= 3\,x_1 \\ x_4 &= 4\,x_1 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Measure the corresponding ordinates T_1, T_2, T_3 and T_4, and calculate the expression

$$z = \sqrt{\frac{T_4 - T_3}{T_2 - T_1}} \quad \ldots \ldots \ldots \quad (2)$$

The ultimate temperature rise, or the distance of PQ from the axis of abscissæ, may be calculated from any one of the four expressions below:

$$\left.\begin{aligned} A &= \frac{T_1}{1 - z} \\ A &= \frac{T_2}{1 - z^2} \\ A &= \frac{T_3}{1 - z^3} \\ A &= \frac{T_4}{1 - z^4} \end{aligned}\right\} \quad \ldots \ldots \ldots \quad (3)$$

It is well to determine A from all the four expressions (3) and to take an average, in order to allow for irregularities of the curve.

If it is desired to continue the curve beyond M, take points $x_5 = 5\,x$, $x_6 = 6\,x$, etc., and calculate the corresponding ordinates T_5, T_6, etc., from the expressions

$$\begin{aligned} A &= \frac{T_5}{1 - z^5} \\ A &= \frac{T_6}{1 - z^6} \quad \ldots \ldots \ldots \quad (4) \\ &\ldots\ldots \\ &\ldots\ldots \end{aligned}$$

which are analogous to (3), and in which A and z are known quantities.

Theory and experience show that heating curves such as OM are exponential curves (see equation (7) in § 496). Therefore, instead of extrapolating by means of the equations (4), OM may be plotted to PQ as abscissæ, using a logarithmic scale. This converts the curve into a straight line which is easily produced to any desired point, and the ordinates replotted to an ordinary scale (see Note on p. 88).

494. Use of the Cooling Curve. — In some cases the "cooling" curve of the transformer is available (Fig. 388), or the curve which gives temperatures of the transformer left to cool, after having been heated, the power being shut off. This curve may be used in addition to the curve OM in order to find the ordinate A and to extrapolate the heating curve beyond the point M. That is, the theory shows (see § 496) that

$$T = A\left(1 - \frac{t}{t_0}\right) \quad \ldots \ldots \ldots \quad (5)$$

where T, as before, is an ordinate of the heating curve, such as DK, t is the corresponding ordinate kD of the cooling curve, and t_0 is the initial temperature on the cooling curve.

The cooling curve is supposed to be given throughout its whole working range; at any rate, being an exponential curve, it may be easily *extrapolated* by being plotted to a logarithmic scale, which converts it into a straight line.

Take a point K for which both $T = DK$ and $t = Dk$ are known; substituting these values in equation (5), determine $A = DN$. Do this for a sufficient number of points on the part OM of the heating curve, so as to be able to draw the line PQ of the ultimate temperature rise with sufficient accuracy. To find points on the heating curve beyond M the same equation (5) is used; the coefficient A is now known, and T can be calculated for any value of t.

It is interesting to note, that any point on the cooling curve may be selected for t_0, because only the ratio t to t_0 enters into calculations, and this ratio is constant for an exponential curve.

The above formulæ and deductions have a practical meaning only when the temperatures of different parts within the transformer are fairly uniform, which is the case in a transformer designed along rational lines. Otherwise, the temperature T in the heating curve has no definite meaning; T for some parts of the transformer may be far beyond the safe limit, though the average T may not be excessive. In oil-filled transformers differences of temperature in different parts are never very great, and it is sufficient for the above purpose, to take the temperature of oil as an indication of the average temperature of the transformer.

495. EXPERIMENT 24-A. — Heat Run on Transformers. — The experiment should be performed on two identical transformers, as in Fig. 387. An auto-transformer with regulating taps may be used for the "booster" transformer C. Insert thermometers into the oil and into the iron and windings; adjust the currents and the voltages to correspond to the desired load.

When performing this test the student should bear in mind that the secondary winding is subjected to a high voltage the instant a low voltage is applied to the primary winding. *Therefore the student must be careful not to put on any voltage whatsoever, until explicitly told to do so by the instructor, and should not touch any windings while the transformer is under test.*

The temperature rise of the windings must be calculated from the increase of resistance, the measurements being performed at the begin-

ning, at the end of the run, and a few times during the test. This is necessary because the thermometers show the temperature of the external part of the insulation only; the temperature inside the coil may be appreciably higher (Fig. 3, Vol. I). The resistance is measured by the drop-of-potential method, using direct current (§ 7). In measuring the resistance during the heat test the readings must be made as rapidly as possible, in order to prevent the transformer from getting cooled off. The best scheme is to have a double-throw switch arranged so that the transformer can be instantly switched from alternating current over to direct current and back. Be sure to remove the voltmeter leads when the current is on and off, because a high induced e.m.f. during the variable state of the current may burn out the voltmeter.

(*a*) Measure the cold resistances, and then begin the temperature run proper. Keep the load constant, read thermometers every five minutes, and from time to time measure resistances, as a check. The time usually allotted for a laboratory experiment is not sufficient for obtaining the final temperature of the transformer. Unless the circumstances allow of taking a continuous run of from 8 to 10 hours, the student will have to extrapolate the heating curve, as explained in § 493. It is well to run the test on an overload, so as to get a sufficient rise of temperature within two or three hours.

(*b*) After the heat test take a core-loss curve within a wide range of voltages. This curve may be of use, should the results of the temperature run show that the temperature rise is too large or too small, for then it is possible to tell by how much to change the voltage (or the current) in order to bring the temperature rise to the desired value. Suppose, for instance, the final temperature rise of a transformer to be 70 degrees C. above the surrounding air. This is more than the safe limit, 50 degrees C., allowed for ordinary transformers. Now the rating of the transformer for continuous load can be figured out as follows: Suppose that the iron loss during the test was 550 watts and the copper loss 850 watts. Thus, a total loss of 1400 watts causes a temperature rise of 70 degrees; the loss that corresponds to a temperature rise of 50 degrees is therefore equal to

$$1400 \times \frac{50}{70} = 1000 \text{ watts,}$$

which allows $1000 - 550 = 450$ watts for copper loss. Consequently, the current during the test was

$$\sqrt{\frac{850}{450}} = 1.37$$

times higher than should be allowed in continuous operation.

It may occur that a transformer is run at such a high voltage that the temperature limit is exceeded at no load, *i.e.* with the iron loss alone. This will show that the transformer has been designed for a lower voltage, or a higher frequency; for the iron loss depends on the flux, and the flux decreases directly with the voltage and inversely with the frequency.

Report. Plot the core-loss curve to volts as abscissæ, and the heating curve to time as abscissæ. Calculate the ultimate temperature rise, as explained in § 493, or according to the method stated in § 494. It may occur that the load or the voltage selected for the test was too high for the transformer, so that the ultimate temperature rise A is beyond that which the insulation of the transformer can safely stand. If this is the case, the student is expected to find out how many hours the transformer can stand this load until the highest allowable temperature rise of 50 degrees C. is reached. Also, what are the maximum load and voltage which the transformer can carry indefinitely; in other words, what should be the true rating of the transformer.

496. Equations of Cooling and Heating Curves. — The mathematical expressions for heating and cooling curves (Fig. 388) will now be deduced. We shall make the assumption that the heat exchange between a warm body and the surrounding air is proportional to the excess of temperature of this body above that of the air. This assumption is confirmed by experience, at least within the limits of temperatures at which electrical machinery is operating.

(*a*) *Cooling Curve.* Let the excess of temperature of a cooling body over that of the air be t degrees Centigrade, and let K be the number of watts radiated in one second, when the difference in temperature between the body and the surrounding air is one degree Centigrade. Then the number of watts radiated during an infinitesimal element of time dx, is

$$Kt.\ dx.$$

On the other hand, if C is the number of watts it is necessary to communicate to the body in order to raise its temperature by one degree Centigrade, and dt is the decrease in temperature during the time dx, the body must have lost Cdt watts, radiated through its surface. Thus, we have

$$Kt\,.\,dx + C\,.\,dt = 0.$$

The integral of this equation is

$$\frac{K}{C}\,x = log\,\frac{t_0}{t},$$

where t_0 is the initial difference of temperature, i.e. when $x = 0$. The integration can be easily checked by differentiating the result. Denoting

the ratio K to C by B, and eliminating the logarithms, we get the following equation of the cooling curve:

$$t = t_0 \cdot e^{-Bx} \quad \ldots \ldots \ldots \quad (6)$$

where e is the basis of Naperian logarithms; B is a coefficient which characterizes the thermal properties of the transformer.

(b) *Heating Curve.* In deducing the equation of the heating curve, we assume that W watts are being continually communicated to the body from an external source, and are converted into heat. In the specific case under consideration, W represents the iron loss and the copper losses in the transformer. The body loses by radiation, as before, $K\,T.\,dx$ watts and its increase in temperature dT is due to the difference $Wdx - KT.\,dx$ watts, or

$$W.\,dx - KT.\,dx = C.\,dT.$$

The integral of this equation is

$$T = A\,(1 - e^{-Bx}) \quad \ldots \ldots \ldots \quad (7)$$

which can be easily checked by differentiating it. In this formula B has the same value as in (6), and $A = W \div C$ is the ultimate temperature rise after an infinite time (Fig. 388). Substituting the value of e^{-Bx} from (6) into (7) the equation of the heating curve is reduced to the following simple form:

$$T = A\left(1 - \frac{t}{t_0}\right) \quad \ldots \ldots \ldots \quad (5)$$

This is the formula used in § 494 above for extrapolating the heating curve.

497. Theory of Extrapolation of Heating Curves.—The method of extrapolation, given in § 493 without proof, may now be deduced from equations (6) and (7).

Writing (7) for the points corresponding to (1), we have:

$$\left.\begin{aligned} T_1 &= A\,(1 - e^{-Bx_1}) \\ T_2 &= A\,(1 - e^{-2Bx_1}) \\ T_3 &= A\,(1 - e^{-3Bx_1}) \\ T_4 &= A\,(1 - e^{-4Bx_1}) \end{aligned}\right\} \quad \ldots \ldots \quad (8)$$

To eliminate A, form the expression

$$\frac{T_4 - T_3}{T_2 - T_1} = \frac{e^{-3Bx_1} - e^{-4Bx_1}}{e^{-Bx_1} - e^{-2Bx_1}} = \frac{e^{-3Bx_1}\,(1 - e^{-Bx_1})}{e^{-Bx_1}\,(1 - e^{-Bx_1})} = e^{-2Bx_1},$$

from which

$$e^{-Bx_1} = \sqrt{\frac{T_4 - T_3}{T_2 - T_1}} \quad \ldots \ldots \ldots \quad (9)$$

this expression is denoted for brevity by z in equation (2).

Substituting (9) in (8) the equations (3) are obtained, and the method is thus proved. Equation (5) is obtained by substituting e^{-Bx} from (6) in (7).

VOLTAGE REGULATION.

498. The term "voltage regulation" generally is used to indicate variations in voltage at the terminals of an apparatus, under different load conditions. More specifically, regulation is defined, in this country, as per cent rise in voltage, when the full rated load is suddenly thrown off the machine, all other conditions remaining the same. Thus, if a transformer gives its rated secondary pressure of 110 volts at full non-inductive load, and the voltage rises to 113 volts when the load is thrown off (the primary voltage being kept constant), the regulation of the transformer by definition is:

$$\frac{113 - 110}{110} = 2.73 \text{ per cent.}$$

The question of regulation is of great practical importance, particularly in case of lighting transformers, where a difference of even two per cent between the no-load and the full-load voltage is quite appreciable in the quality and quantity of light given by incandescent lamps. In transformers used on power circuits this is not so important, except where incandescent lamps are connected to the same circuit. In this case the requirements for regulation must be very strict, because the inherent regulation of a transformer on inductive loads is worse than on non-inductive load.

In many cases it is difficult to measure voltage drop and regulation under actual load conditions. Take, for instance, the case of a 2000-kw., 60,000 to 10,000-volt transformer: It is difficult to find a rheostat for loading such a transformer, and also a voltmeter that would measure a few per cent drop at such voltages with sufficient accuracy.

Therefore a method has been devised which permits the *pre-determination* or calculation of the regulation of a transformer from a simple *short-circuit test.* Such a test requires power to but a few per cent of the rated capacity of the apparatus, and may be performed with a comparatively low voltage. The method is analogous to that described in § 467 for the predetermination of regulation of transmission lines.

499. Predetermination of Regulation of a Transformer. — Voltage drop in a transformer is caused chiefly by the inductance of the windings; also to some extent by their ohmic resistance. The inductance is caused by leakage fluxes, which surround one of the windings, without being interlinked with the other winding.

It is very difficult, if not impossible, to separate the primary inductance in a transformer from the secondary; fortunately, this is not necessary for predetermining the regulation of a transformer, since the primary and the secondary inductances act together as one *equivalent* inductance. This combined or equivalent inductance can be easily determined from a short-circuit test, similar to that described in § 467 in application to transmission lines; the only difference being that the transformer circuit, instead of being continuous, consists of two parts connected by a magnetic link, or the useful magnetic flux of the transformer (Fig. 241). This, however, affects the results only in so far that the energy appears in the secondary circuit at a different voltage, depending on the ratio of turns, primary and secondary.

Thus, instead of considering the primary and the secondary impedances separately, the secondary impedance may be imagined transferred into the primary circuit (Fig. 389).

When making this transfer both the secondary resistance r_2 and the reactance x_2 must be multiplied by the square of the ratio of numbers of

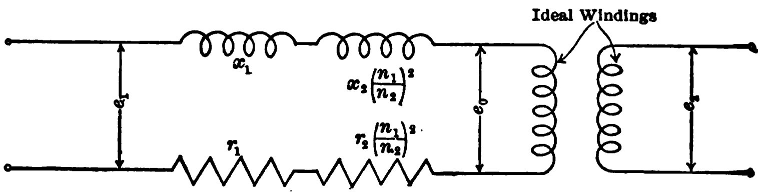


FIG. 389. Equivalent resistance and equivalent reactance of a transformer.

turns, $= (n_1/n_2)^2$. A proof of this is given in the next article. We have now an ideal transformer without any drop, and some resistance and inductance in series with it. The problem of predetermining the regulation is the same as in the case of a transmission line. The combined or equivalent impedance of the transformer is determined by short-circuiting one side of it and applying a low voltage to the other side. From the measured current and voltage, a triangle is constructed, as in Fig. 369. The resistances are measured separately with direct current, and the reactance $x_1 + x_2. (n_1/n_2)^2$ thus calculated, is used for the predetermination of regulation at different loads, as in the case of a transmission line.

500. Transferring Resistances from Primary into Secondary. — The above given method for transferring the secondary impedance into the primary circuit is based on the general property of the transformer, that two resistances, differing from each other in the ratio $(n_1/n_2)^2$, being inserted into the primary and the secondary circuits respectively,

give the same per cent drop. Let R_1 be a resistance inserted into the primary circuit, and R_2 another resistance connected in series with the secondary circuit. Per cent voltage drop caused by the first resistance is $i_1 R_1/e_1$ and that caused by the second resistance is $i_2 R_2/e_2$. Remembering that

$$i_1 n_1 = i_2 n_2, \text{ and } \frac{e_1}{e_2} = \frac{n_1}{n_2}$$

we find that these two expressions are identical if

$$R_2 = R_1 \left(\frac{n_2}{n_1}\right)^2.$$

This means that resistances (ohmic or inductive) may, for purposes of computation, be considered transferred from the primary circuit into the secondary, provided they are reduced as the square of the ratio of the number of turns. In other words, the resistance R_1 gives the same per cent drop in the primary circuit as a resistance $R_1 (n_2/n_1)^2$ in the secondary circuit; in problems, where voltage drop and regulation alone are considered, these two resistances may be used indiscriminately. Another proof based on considering the actual vector diagram of the transformer is given in § 503 below.

501. Example of Predetermination of Regulation.—After these preliminary considerations it can be shown, in an example, how to predetermine the regulation of a transformer. First of all, determine as accurately as possible its ratio of transformation at no load. Let it be 2200 to 110 volts; then measure the ohmic resistances of both windings, using direct current (drop-of-potential method). Let the resistance of the primary be 1.05 ohms, and that of the secondary = 0.002 ohm. Now short-circuit the secondary (low-tension) terminals and apply at the primary terminals a voltage sufficient to produce a considerable current in the windings. It is advisable to short-circuit the secondary winding through an ammeter in order to be able to read the current in it; in figuring out the results, the resistance of the ammeter must be added to that of the secondary winding. Let the applied pressure be 120 volts, and the currents, primary and secondary, 25 amperes and 500 amperes. The currents are almost exactly in the same ratio as the no-load voltages. If the resistance of the secondary ammeter is 0.001 ohm, the total secondary resistance is 0.003 ohm, or, reduced to the primary circuit, $0.003 \times 20^2 = 1.2$ ohms. Thus, the total equivalent ohmic resistance of the transformer, reduced to the primary circuit is $1.05 + 1.2 = 2.25$ ohms.

Now with reference to Fig. 369 we can say: the total applied voltage $E_0 = 120$ volts is used partly for overcoming the equivalent ohmic drop of the transformer, partly by its equivalent reactance. The first drop is equal to $2.25 \times 25 = 56.2$ volts; therefore the reactance drop is

$$\sqrt{(120)^2 - (56.2)^2} = 105.7 \text{ volts};$$

hence the equivalent reactance, reduced to the primary circuit, is

$$\frac{105.7}{25} = 4.23 \text{ ohms}.$$

Let it be required to predetermine the regulation of this transformer at a constant secondary voltage of 110 volts, an output of 70 kw., and a power factor of 80 per cent. The secondary current is

$$\frac{70{,}000}{110 \times 80} = 796 \text{ amperes},$$

or, reduced to the primary circuit, $796/20 = 39.8$ amperes. The voltage e_0 at the primary terminals of the ideal transformer (Fig. 389) is 2200 volts. The equivalent ohmic drop $= 2.25 \times 39.8 = 89.5$ volts; the equivalent reactive drop $= 4.23 \times 39.8 = 169$ volts. We now construct the diagram, as in Fig. 364, and find that the voltage e_1 (Fig. 389) is 2370 volts. The same result follows from formula (5) in §§ 459 and 469:

$$e_1^2 = (2200 \times .80 + 89.5)^2 + (2200 \times .60 + 169)^2$$

from which $e_1 = 2370$ volts. At no load this voltage produces a secondary pressure of

$$\frac{2370}{20} = 118.5 \text{ volts};$$

therefore, by definition, the regulation of the transformer at this particular load is

$$\frac{118.5 - 110}{110} = 7.7 \text{ per cent}.$$

502. EXPERIMENT 24-B. — Regulation of a Transformer from Short-Circuit Test. — The experiment is performed as explained in the preceding article. If possible, the student should obtain, very accurately, at least one set of voltmeter readings on actual load, preferably on an overload with a low power factor (most unfavorable conditions), so as to check the predetermined regulation with that observed experimentally.

In addition to these tests it is desired that the student verify the above deduced law (§ 500), that resistances can be transferred from the primary circuit into the secondary by multiplying them by the square of the ratio of number of turns. This can be tried either during the short-circuit test, or during the load test. Connect a certain resistance in series with the secondary circuit so as to reduce the secondary voltage to a certain value. Then reduce the voltage to the same value by inserting some resistance into the primary circuit. Measure the two resistances and see if they satisfy the above rule. Perform the same test with two reactances.

Report. Construct Kapp's diagram, as explained in § 504, and plot per cent regulation with full-load current, to power factor as abscissæ. Show how closely the predetermined regulation checks with the observed. Give experimental results with regard to transferring resistances from the primary into the secondary circuit.

503. Vector Diagram of Transformer. — Actual relations of currents and voltages in a transformer are shown in Fig. 390. The horizontal line represents the vector of the useful flux, common to both windings; the vectors of the two induced e.m.f.'s, OE_1 and OE_2, are perpendicular to the vector of the flux; also, $OE_1 \div OE_2 = n_1 \div n_2$. The vector i_2 of the secondary current lags behind the terminal voltage e_2 by an angle ϕ_2 depending on the load. The vector of the primary current i_1 is directly opposite to i_2 (neglecting the magnetizing component) and $i_1 \div i_2 = n_2 \div n_1$. The applied primary voltage $OA_1 = e_1$ is larger than OE_1 by the amount E_1A_1 representing the primary drop. E_1A_1 consists of the ohmic component $E_1B_1 = i_1r_1$, and of the reactive component $B_1A_1 = i_1x_1$. The first vector is parallel to the vector of the current i_1, the second is perpendicular to it.

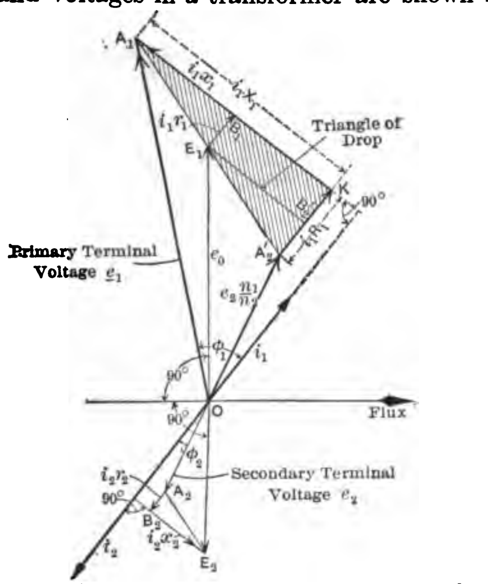


FIG. 390. Performance diagram of a transformer; the cross-hatched triangle represents the total drop.

The voltage OA_2 at the secondary terminals is smaller than the induced secondary e.m.f. OE_2 by the amount E_2A_2 representing the secondary drop. This drop again consists of two components, i_2r_2 parallel, and i_2x_2 perpendicular to the vector of the current i_2.

It will be noted, that the vector of the primary drop, E_1A_1, is added to the primary e.m.f., while the secondary drop E_2A_2 is subtracted from the secondary e.m.f. This is because the voltage at the primary terminals must overcome not only the counter-e.m.f. of the transformer, but the drop as well. On the contrary, there is no counter-e.m.f. in the secondary circuit, and the voltage available for the load is equal to that induced in the transformer, less the amount lost in its secondary impedance.

For practical purposes it is important to know the relation between the terminal voltages OA_1 and OA_2, and not between the induced voltages OE_1 and OE_2, which cannot be measured. To eliminate the latter, multiply all the sides of the polygon $OE_2B_2A_2$ by the ratio $n_1 \div n_2$ and substitute $(i_1n_1 \div n_2)$ for i_2; then turn the polygon over into such a position, that OE_2 coincides with OE_1. The new position of the polygon is $OE_1B'_2A'_2$. Completing the figure OA'_2KA_1 the relation may be obtained between the primary terminal voltage OA_1 and the secondary terminal voltage OA'_2 (reduced to the primary circuit). The difference between the two, or the total *equivalent* drop in the transformer, is represented by the vector A'_2A_1. This drop can be resolved into an equivalent ohmic component A'_2K and a reactive component KA_1. It will be easily seen from the figure that $i_1R_1 = A'_2K = A'_2B'_2 + E_1B_1 = A'_2B'_2 + i_1r_1$. But $A'_2B'_2 = A_2B_2\,(n_1 \div n_2) = i_2r_2\,(n_1 \div n_2) = i_1r_2\,(n_1 \div n_2)^2$. Substituting and dividing by i_1, we get:

$$\text{Equivalent ohmic resistance, } R_1 = r_1 + r_2\,(n_1 \div n_2)^2.$$

Analogously, we obtain

$$\text{Equivalent reactance, } X_1 = x_1 + x_2\,(n_1 \div n_2)^2.$$

The same expressions are developed in § 500, except that the equivalent resistance is there reduced to the secondary circuit. The above deduction can therefore be considered as another proof of the proposition that resistances and inductances can be transferred from one circuit into the other, when multiplied by the square of the ratio of the number of turns.

504. Kapp's Diagram. — It would be a tedious process to construct the diagram Fig. 390 separately for different values of load and power factor. With a certain value of current, the triangle A'_2KA_1 is independent of the power factor, the only variable being the angle ϕ_2 between the terminal voltage and the current. Dr. G. Kapp suggested a modification of the above diagram (Fig. 391), convenient for pre-

determining regulation at a given current with varying power factor of the load. The triangle OKC in Fig. 391 is the same as the triangle A'_2KA_1 in Fig. 390. In either case it is constructed from the result of a short-circuit test (Fig. 369). OE_r is the direction of the vector of the current, primary and secondary. The primary line voltage e_1 being constant, a semicircle is described from C as a center, with a radius equal to e_1. To find the secondary voltage e_2 (reduced to the primary circuit) draw the vector OE at an angle ϕ_2 corresponding to the power factor of the load. The length OE gives the value of the secondary voltage corresponding to this power factor.

With purely inductive load, the secondary voltage is a minimum, and is represented by the vector OE_x perpendicular to i. With a non-inductive load, the secondary terminal voltage is equal to OE in phase with the current OI. In case of a pure capacity load, the secondary voltage is equal to OE_c; it is larger than the applied voltage e_1 (reduced to the same number of turns). This is due to a partial resonance between the capacity of the load and the inductance of the transformer itself (see § 443).

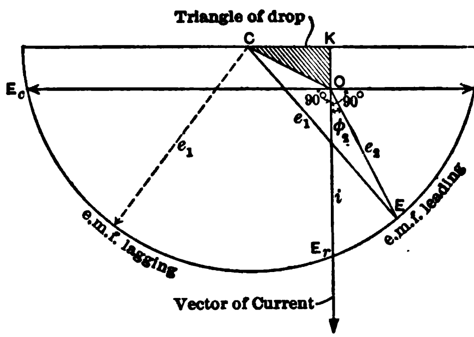


FIG. 391. Kapp's diagram of voltage drop and regulation.

If the secondary instead of the primary voltage is constant, a semicircle must be drawn from O as a center; the vectors from C to the intersection with this semicircle then give the values of the primary voltage necessary for maintaining the required secondary voltage with a varying power factor.

For other values of current, the triangle OKC must be changed correspondingly; the rest of the diagram remains the same.

The difficulty in applying Kapp's diagram to actual transformers is that the triangle OKC is comparatively small, and therefore the difference between OE and CE cannot be measured with sufficient accuracy. For this reason some prefer to express analytically the relations shown in Fig. 390 and to figure out the required voltage from a formula similar to that given in § 459. Another solution is to use tables and charts mentioned in § 468, by means of which per cent voltages are read off directly for given percentages of ohmic and inductive drop, and at any current and power factor.

TESTING INSULATION.

505. Samples of insulating materials used in the construction of electrical machinery are tested for dielectric strength before the materials are accepted. This is done by applying to the sample a high voltage until it is pierced through by the electric spark. This is similar to testing mechanical strength of materials. In using insulating materials a factor of safety is assumed, as in the case of structural iron or machine parts. Thus, for instance, a sample of insulation which can stand 10,000 volts as a limit would not be used for a strain higher than 2000 volts in a lighting transformer, thus allowing for a factor of safety equal to five.

The most important materials used as electrical insulation are impregnated cloths and fabrics, treated paper and other fibrous materials, rubber, glass, porcelain and mica. Wire used for windings is usually double-cotton insulated (magnet wire); the coils, after being wound, are impregnated with special insulating varnishes which increase the insulating properties of the cotton and preserve it from atmospheric influences. A great majority of modern transformers and high-tension switches are oil-immersed, so that oil must be added to the list of insulating materials.

High voltages necessary for testing are obtained by means of special transformers (Fig. 392), so-called testing transformers. No large output is required of such transformers, but they must give very high voltages, and these voltages must be easily adjustable within a wide range.

The description and tests given below are intended to familiarize the student with the properties of various insulating materials, rather than with the methods of testing insulation of actual transformers. The reasons are: (1) The student is naturally interested in determining the point at which a transformer "breaks down"; no school could afford to supply transformers for such tests. (2) The ability of a transformer to stand an over-potential depends upon the combined action of more than one insulating material used in it; the beginner should first become familiar with the properties of each material separately.

506. Description of a Testing Transformer. — A convenient arrangement for testing insulation, as well as for other high-tension experiments, is shown in Fig. 392. Two transformers are used: one is the testing transformer proper, the other serves for regulating the voltage. To insure a better insulation the testing transformer should preferably have no taps. It is well to interpose a third transformer, the so-called insulating transformer, with a "one to one" ratio between the

regulating and the testing transformer; this is an additional safeguard to the operator in case of defective insulation. The sample *I* to be tested is placed in the glass case *GG*. The switches *kk*, mounted on the doors of the case, are connected into the low-tension supply circuit. This is done for the safety of the operator: in order to reach the sample,

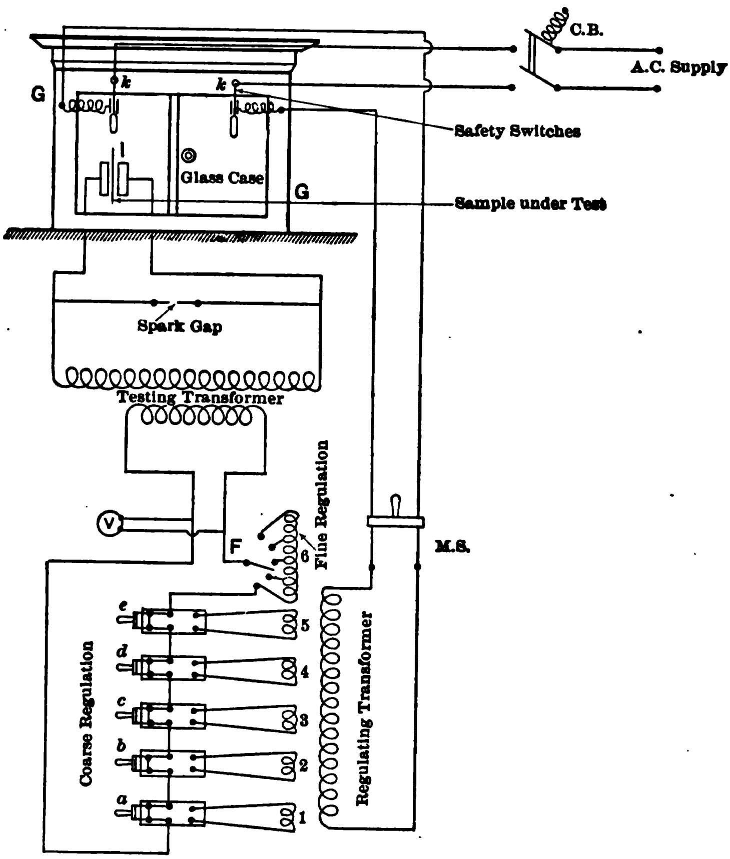


FIG. 392. Diagram of connections for disruptive tests on insulation.

he has to open the doors of the glass case, and to do this he has to open the switches *kk*, thus disconnecting the transformer from the source of supply.

The details of the circuit are as follows: The current from a low-pressure supply passes through the circuit-breaker C. B. and through the above-mentioned safety switches *kk* to the main switch M. S. and to the primary of the regulating transformer. The secondary of this transformer is wound in six sections, five of them being used for coarse

regulation and the sixth for fine regulation. Coarse regulation is obtained by throwing the switches *a*, *b*, *c*, *d* and *e* to the right; fine regulation is done by the handle *F*. The secondary of the regulating transformer is connected directly to the primary of the testing transformer, the voltage being here raised many times. For instance, the regulating transformer may be made to raise the voltage from 110 to 2000 volts, and the testing transformer wound with the ratio 100:1; such a combination gives testing voltages up to 200,000 volts.

The electric pressure across the sample under test is measured by the voltmeter *V* connected to the low-tension side of the testing transformer, it being only necessary to multiply voltmeter indications by the ratio of transformation. Sometimes a spark gap is used in parallel with sample under test, as shown in the sketch. A table may be found in the *Standardization Rules of the American Institute of Electrical Engineers*, giving sparking distances for various voltages up to 300,000 volts. Some engineers do not trust the spark gap, and object to its being used. A spark gap is, however, a good precaution against an accidental rise of voltage beyond a desired limit; as soon as this limit is reached a spark jumps across the gap and the rush of current opens the circuit-breaker on the low-tension side.

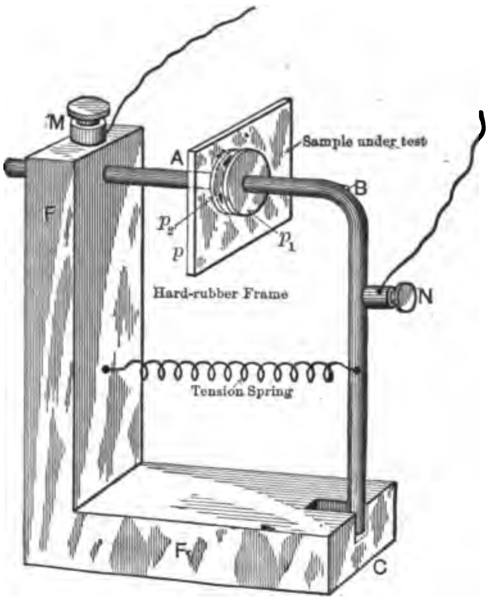


FIG. 393. A clamp for testing insulation.

507. Disruptive Strength of Solid Dielectrics, Compounds, and Oil. — Materials like Fuller-board, cloth, mica, etc., may be conveniently tested in a clamp, shown in Fig. 393. The frame *FF* of the clamp is made of hard-rubber, the metal parts of brass. The tension spring insures the same tension being applied to the samples in all cases; the terminal plates p_1, p_2 have a loose fit in the supports and adapt themselves to the surface of the sample under test.

The disruptive strength of insulating materials is affected by many causes: In the first place it depends on the thickness of the sample; it

could be naturally expected that a double thickness of insulation can stand a double voltage, but experience shows that this is not the case, and that the resistance to puncture increases more slowly than the thickness. If, for instance, a sample 0.01″ thick can stand 10,000 volts, a sample 0.02″ thick will be punctured at less than 20,000 volts. The cause of this is not definitely known; possibly, it is due to thicker samples being not as homogeneous inside as thinner ones. At any rate, several thin samples put together can stand more than one thick piece; therefore, the more important parts of insulation of high-tension transformers are always built of many thin layers, and not of a thick piece of insulation which may have faults inside. Mr. Baur, on the basis of his numerous tests, announced an empirical law (Baur's law) that dielectric strength increases as $d^{\frac{2}{3}}$ where d is the thickness of the insulating material. According to this law if a sample 1 mm. thick can stand 5,000 volts it takes a sample $2^{\frac{3}{2}}$ or about 2.8 mm. thick to stand 10,000 volts. Another investigator, Dr. Walter, assumes the law to be:

$$\text{break-down voltage} = a + bd,$$

where a and b are constants. This formula can be interpreted by saying that, in addition to the voltage bd for breaking the material proper, it takes an extra voltage a independent of the thickness of the sample to break its surfaces. It would be premature to decide between the two formulæ on the basis of the experimental data on hand. The only established fact is that the dielectric strength increases more slowly than the thickness; therefore, in all important cases tests should be performed on samples of exactly the same material that is intended to be used in the machine.

The other two factors which considerably influence the strength of insulation are: presence of moisture, and heat. Most of the insulating materials lose to a large extent their good insulating properties when subjected to moisture, or when they have not been sufficiently dried out before being used; also when heated up beyond a certain temperature.

Insulating varnishes, paints and impregnating compounds are tested by applying them in an even layer on some kind of cloth (preferably linen) and subjecting the cloth to a break-down test. By using always the same kind of cloth, testing it without varnish and with different kinds of varnishes, various brands can be compared, by the increase in the dielectric strength of the cloth.

Insulating oil is conveniently tested in the apparatus shown in Fig. 394, devised by Mr. C. E. Skinner. It consists of a glass tube *A*, filled with a definite quantity of oil under test, with two brass balls immersed

in it as electrodes. These balls are set at a definite distance apart by means of a micrometer *D* placed on top of the apparatus, and an electric pressure is applied between them until a spark jumps through the oil. This break-down voltage is taken as a measure for the dielectric strength of the oil. By testing different oils in the same vessel, and with the same distance between the balls, a direct comparison of different kinds of oil is made possible. After each test the oil must be thoroughly shaken so as to mix with it the carbon formed by the electric arc. The brass balls must be kept well polished, as the sparking distance depends essentially on the state of their surfaces.

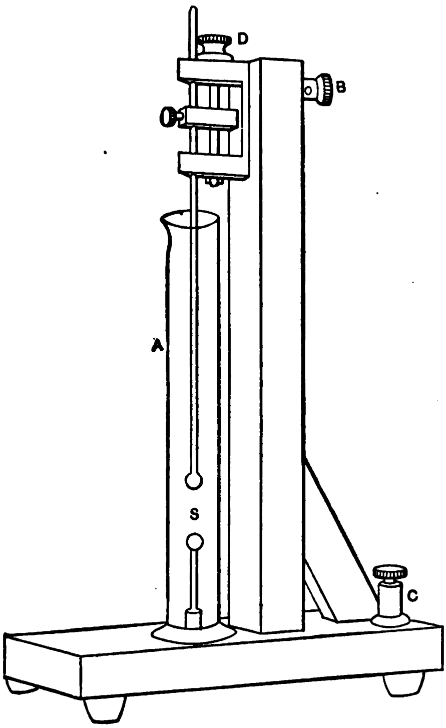


FIG. 394. A vessel for testing dielectric strength of oil.

For oil tests, other than disruptive strength, see an article in the *Electric Club Journal,* 1904, p. 227.

508. EXPERIMENT 24-C. — Insulation Tests with a High Tension Transformer.— The purpose of the experiment is to afford experience in handling a high-tension transformer, and also to learn the principal properties of insulating materials used in electrical work. Before beginning the tests proper, the student should study most carefully the connections of the testing set, and be sure that all high-tension parts are properly insulated. The voltages used for test are dangerous to life, and utmost precautions and concentration of attention are required while performing the test.

Begin the experiment by puncturing a few samples of different materials, merely to observe the behavior of the transformer, of the circuit-breaker, spark gap, etc., and to get a general idea of the magnitudes of the pressures involved. After this, make systematic tests on one material, such as fiber, treated paper or cambric, etc. Use material of different thickness, and also several layers of the same or different materials as a compound insulation. Then the student may slightly

moisten a few samples, or heat them and see how this affects their dielectric strength.

It will be observed that these materials differ widely in the maximum voltage which they can stand, mica being the best insulator, and fiber and wood the poorest, they being punctured at many times lower pressure than mica, with the same thickness of the sample. Other insulating materials, Fuller board, treated paper, Empire cloth, etc., have disruptive strengths between these extremes. Different samples, taken even from the same piece of material, may give considerable discrepancies in results due to a lack of uniformity of structure and accidental impurities and faults. Reliable results can be obtained only as an average of hundreds of tests made on the same material, by a skilled observer. All that is expected from the student in this exercise is to get a few comparative data on the strength of different materials, and to learn how to handle a high-tension testing transformer.

Oil is tested as is described in the preceding article. In order that the student may see the importance of oil as insulation he should compare the voltage at which a spark jumps between the two brass balls in the oil-testing apparatus, with and without oil. It will be found that the voltage is much higher when the balls are immersed in oil. Having tested a sample of oil, add to it a few drops of water and see how markedly it affects the insulating properties of the oil; the same thing will be observed if a small amount of acid is added.

It is recommended that the student also puncture some other kinds of insulation important in electrical work, for instance, porcelain insulators, and insulated wires used on electric lines. These articles are tested under the most unfavorable conditions met with in practice, namely *wet*. Insulators are turned upside down and immersed in salt water which serves as one terminal; the other terminal is applied to the inside of the insulator, also filled with water. Insulated wires are tested immersed in water, the pressure being applied between the core and the water; it is required that the wire be immersed for twenty-four hours before the test.

Purely electrical tests as described above are not sufficient for finally approving an insulating material for use. It must possess, in addition, certain mechanical and chemical properties without which it could not be used in commercial apparatus. Thus, for instance, solid insulators should not be brittle, or affected by acid and fumes; they should be easily machined, not deteriorate with time, etc. All such tests are, for obvious reasons, outside the scope of the above laboratory exercise.

References. A very clear and complete book on *The Insulation of Electric Machines* is that by Turner and Hobart. This book contains

most of the noteworthy results obtained by different investigators of insulating materials; moreover, it contains a complete bibliography on the subject (pp. 272–279). Chapter II of this book, treating on general properties of insulating materials, may be consulted in connection with this exercise, and also Chapter XXII, "Specifications for Insulation." The rest of the book is devoted to a detailed description of properties, tests and processes of manufacture of various insulating materials. Recommendations of the American Institute of Electrical Engineers in regard to testing for dielectric strength may be found in the report of their Committee on Standardization. For a series of good articles by Mr. C. E. Skinner, on testing insulation, see the *Electric Journal*, 1905, beginning on p. 615. See also Wernicke, *Die Isoliermittel der Elektrotechnik* (Vieweg & Sohn).

NOTE TO PAGE 70. Two common mistakes that a beginner is liable to make are: (1) to use ordinary logarithmic paper on which both abscissæ and ordinates are divided according to the logarithmic law; (2) to plot the heating curve to a logarithmic scale, using as ordinates the values of T instead of $(A - T)$. In either case he will fail to get a straight line. The correct procedure is to use as ordinates values of $(A - T)$ plotted to a *logarithmic* scale, against time x as abscissæ plotted to an ordinary *proportional* scale. Such a scale is easily marked on ordinary logarithmic paper.

The above-stated rule follows from eq. (7), which can be reduced to the form

$$e^{Bx} = \frac{A}{A - T}.$$

Taking the logarithms of both sides of this equation we get

$$Bx = \log A - \log (A - T);$$

in other words, the straight-line law exists between x and the logarithm of $(A - T)$.

CHAPTER XXV.

ELECTRICAL RELATIONS IN POLYPHASE SYSTEMS.

509. A SIMPLE alternating current is entirely satisfactory for lighting, but up to this time the inventors have been unable to construct a satisfactory single-phase motor for ordinary commercial work. The single-phase commutator-motor is well adapted for railway work only, and the single-phase induction motor, although used to some extent, is not a satisfactory machine, except in small sizes. But, if the actions of *two or more alternating currents differing in phase are combined in one motor*, the motor is much improved, because *at no time is the power equal to zero* in all component circuits, or phases, at once.

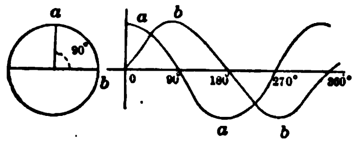


FIG. 395. Graphical representation of a two-phase system.

Such combinations of alternating currents, differing in phase and mutually interlinked into one system, are called *polyphase systems*; their origin was a demand for a good alternating-current motor. Two types of motors are used on polyphase circuits: induction motors, based on the familiar principle of the revolving magnetic field; and synchronous motors, which are inverted polyphase alternators.

510. The Two-Phase System and the Three-Phase System. — Of all the possible combinations of alternating currents only the two simplest ones came into general use: the *two-phase system*, consisting of two currents with a phase displacement of 90 degrees, or quarter of a period (Fig. 395); and the *three-phase* system, consisting of three currents symmetrically displaced in phase by 120 degrees, or one-third of a period (Fig. 396). In these figures the sine-waves represent the instantaneous values of currents in separate phases, plotted to time as abscissæ. The time is expressed in degrees, one complete period of alternating current being equivalent to 360 electrical degrees. Instead of actually plotting the sine-waves the same relations are represented

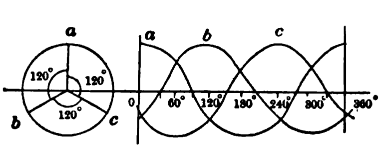


FIG. 396. Graphical representation of a three-phase system.

more simply by the radii or vectors drawn 120 or 90 degrees apart (see Figs. 399 and 406).

The understanding of electrical relations is easier in the two-phase system than in the three-phase system, because the former may be considered as a combination of two simple alternating-current circuits; volts, amperes and watts can be measured in each phase separately. For this reason the two-phase system is considered first.*

TWO-PHASE SYSTEM.

511. The principal combinations of two single-phase circuits into a two-phase system are:

Two independent phases, Fig. 397;

Two-phase three-wire system, Fig. 398;

Quarter-phase, star connection, Fig. 402;

Quarter-phase, mesh connection, Fig. 403.

In so far as the use of the line itself is concerned, all the above enumerated systems are electrically equivalent; the only difference is in the inside connections of generators and receiving devices.

The two-phase four-wire system is the one most commonly used, especially when, in addition to motors, a considerable amount of lighting is to be supplied; for the latter, each phase is used separately, the lamps being divided into two groups. The three-wire system gives a greater economy in copper, and reduces the number of insulators on the poles, but it has the disadvantage of being unsymmetrical. The quarter-phase star connection is used when it is desired to have a neutral point, for instance in case of a three-wire direct-current line fed from a two-phase rotary converter (Fig. 206). The quarter-phase mesh-connected system is obtained when a direct-current armature is tapped off at four equidistant points for producing two-phase currents. Such is the case in two-phase rotary converters and some revolving-armature alternators.

The electrical relations in all these varieties of the two-phase system will now be taken up more in detail.

512. Two Independent Phases. — This system is shown in Fig. 397; one-half of the total power is transmitted through each phase. The phases are entirely independent of each other, their only relation being that a phase difference of 90 degrees is maintained between the two

* A small experimental alternator, convenient for studying relations in polyphase systems, is made by the General Electric Company, especially for colleges. It has six independent armature windings with twelve leads brought out. By suitably connecting these leads, single-phase, two-phase and three-phase combinations may be produced, and voltages varied within wide limits.

by a suitable disposition of the armature windings in the alternator (Fig. 453). This phase relation comes into play in the windings of the motors supplied from the two-phase line, where the two currents produce a revolving magnetic field.

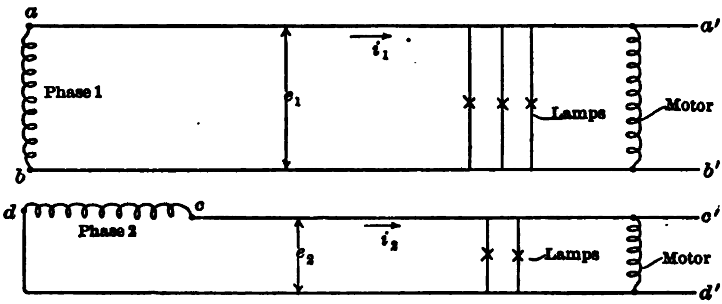


FIG. 397. Two-phase four-wire system.

The relations between the current, the voltage and the power in each phase are exactly the same as in an ordinary single-phase line.

513. EXPERIMENT 25-A. — Electrical Relations in a Two-Phase Four-Wire System. — Wire up and load a two-phase alternator as per Fig. 397. Measure power in each phase independently, and determine the total power delivered by the machine with balanced and with unbalanced load. Connect the generator to a two-phase induction motor in order to see the production of a revolving field. Observe the effect produced on the motor by reversing one of the phases, or both phases. Report the data and the phenomena observed.

514. Two-Phase Three-Wire System. — The connections are shown in Fig. 398; this system is obtained by connecting two wires bb'

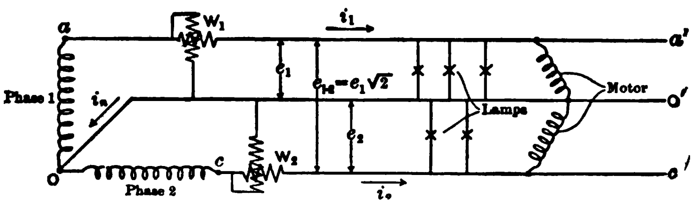


FIG. 398. Two-phase three-wire system.

and dd' (Fig. 397), belonging to different phases, into one, OO', which is called the common return wire.

(*a*) The electrical relations with *balanced non-inductive load* are shown in Fig. 399. The currents i_1 and i_2 are represented by two vec-

tors displaced by 90 degrees. The current in the return wire is equal to the sum of the two, and is therefore represented by the diagonal i_n. The load being non-inductive, the line voltages e_1 and e_2 are in phase with the corresponding currents. The voltage e_{1-2} between the two outside wires, being a geometrical difference between the two-phase voltages, is represented by a vector connecting the extremities of the vectors e_1 and e_2. It will be seen from the diagram that $i_n = i_1 . \sqrt{2} = i_2 . \sqrt{2}$, and $e_{1-2} = e_1\sqrt{2} = e_2\sqrt{2}$.

The student must clearly understand that the current i_n is a geometrical *sum* of the two-phase currents, while the voltage e_{1-2} is a geometrical *difference* between the two-phase voltages. The reason for this may be seen by considering instantaneous values. If 5 amperes are flowing at a certain instant through the wire aa' (Fig. 398), and 3 amperes in the wire cc', in the same direction, 8 amperes must flow back into the generator through the common return wire OO'. It is different in the case of voltages; suppose that the common return wire is grounded and the potential of the wire aa' at a certain moment is 100 volts above the ground, while the potential of the wire cc' is only 40 volts above the ground. It is evident, then, that the difference of potential between the two wires is $100-40=60$ volts. Thus we must add currents and subtract voltages. The relations which are true algebraically for *instantaneous* values are true geometrically for the vectors of *effective values;* this explains the construction in Fig. 399.

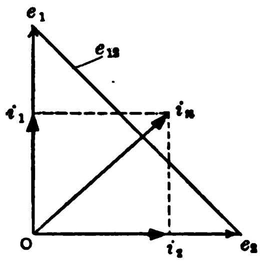


FIG. 399. Current and voltage relations in a two-phase system at a balanced load.

(*b*) When the *load is inductive,* the currents i_1 and i_2 (Fig. 400) are no longer in phase with the corresponding voltages, but are lagging behind by certain angles ϕ_1 and ϕ_2. The current i_n in the common return wire is a geometrical sum of the two, as before. The load may be different in the two phases; this is shown in the diagram by the vectors i_1 and i_2, being of different lengths and lagging by different angles (unbalanced load).

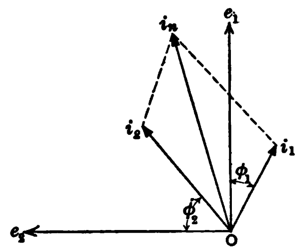


FIG. 400. Current and voltage relations in a two phase system at an unbalanced load.

(*c*) *The resistance of the common return wire* is not always negligible, as is presupposed in the above diagrams. The diagram, shown in

Fig. 401, explains the way in which this resistance is taken into account. Assuming the load to be non-inductive and balanced, the vector of the voltage drop $e_n = i_n r_n$ in the return wire is in phase with the current i_n and at equal angles with both phase voltages e_1 and e_2. Subtracting this drop from the phase voltages, as is shown by the two vectors $-e_n$, we obtain the pressures available at the receiving end of the line. With non-inductive load, the currents i_1 and i_2 are in phase with these voltages, and the sum of the two currents is the current i_n.

It will thus be seen that the effect of the resistance of the common return wire is to reduce the phase voltages and to increase the phase angle between them. If it is necessary to take into account also the voltage drop in the phase wires aa' and cc', the vectors of this drop are subtracted geometrically from the generator voltages e_1 and e_2.

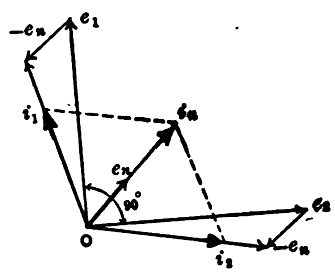


FIG. 401. Current and voltage relations in a two-phase system, taking into account the resistance of the return wire.

(*d*) *Electric power* is measured in the three-wire two-phase system by two wattmeters, as shown in Fig. 398. The sum of two readings gives the total power delivered by the generator. This is true for balanced as well as for unbalanced or inductive loads, for, even here, each phase may be considered independently.

515. EXPERIMENT 25-B. — Electrical Relations in Two-Phase Three-Wire System. — The purpose of the experiment is to make clear the electrical relations explained in the preceding article. Connect up the alternator and the load as per Fig. 398 and provide an ammeter, a voltmeter and a wattmeter which, by means of a suitable polyphase board (§ 49), may be connected into any of the wires. Perform the measurements in the following order:

(*a*) Balanced non-inductive load, relations as per Fig. 399.

(*b*) Unbalanced non-inductive load; same figure, but the vectors i_1 and i_2 are of different lengths.

(*c*) Inductive load, balanced and unbalanced, Fig. 400.

(*d*) Line wires and return wire of considerable resistance; relations as per Fig. 401.

Measure carefully volts, amperes and watts, so as to be able to construct the corresponding diagrams.

Report. Show in how far the theoretical relations indicated in Figs. 399 to 401 check with the results of actual measurements.

516. Quarter-Phase System, Star Connection.—This system (Fig. 402) is obtained from the four-wire system shown in Fig. 397 by connecting the middle points of the two phase-windings. Three kinds of voltages must be distinguished in the quarter-phase system:

(1) Phase voltages, e_1 and e_2; these are the same as in the four-wire system, or in a three-wire system.

(2) Star voltages, e_0, between the neutral point O and the points a, b, c, and d. It is easily seen that the star voltages are equal to one half the phase voltages.

(3) Mesh, or interlinked, voltages between the wires belonging to different phases, such, for instance, as between a and c, or a and d. The voltage between a and d is the geometrical difference between the voltages Oa and Od (see § 514). Constructing a diagram similar to

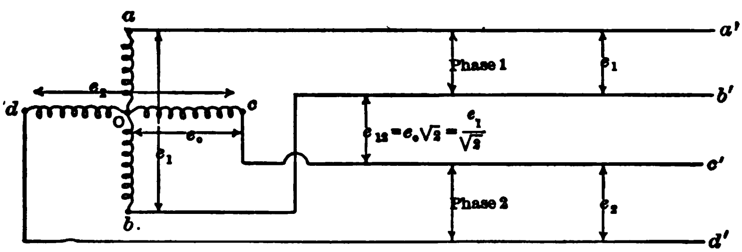


FIG. 402. Quarter-phase system, star connected.

that shown in Fig. 399 it may be easily proven that the mesh voltage $e_{1-2} = e_0\sqrt{2} = e_1/\sqrt{2}$. The current and power relations are the same as with two independent phases.

517. EXPERIMENT 25-C. — Electrical Relations in Quarter-Phase Star-Connected System. — Either the generator or the load, or both, should be connected in star, as per Fig. 402. If the middle points of the generator windings are not accessible, connect only the load in star. Balance the load and measure the three kinds of voltages mentioned in the preceding article. Then unbalance the load so as to make all the four star voltages different, and again measure all the currents, voltages and watts in order to be able to determine the phase angles. Perform similar measurements with an inductive load.

Report. Show how close the actual ratios between the voltages at balanced load are to be theoretical ratio $\sqrt{2}$. Construct diagrams showing the relations with unbalanced and inductive load. The vectors of the four mesh-voltages form a square (Fig. 404) of which the phase voltages are the diagonals. The star voltages are represented by the vectors drawn from a point inside of the square to

its vertices. At balanced load this point coincides with the intersection of the diagonals; at unbalanced load the two points are different.

518. Quarter-Phase System, Mesh Connection. — The connections are shown in Fig. 403. Two kinds of voltages are distinguished:

(1) Phase voltages, e_1 and e_2.

(2) Mesh or interlinked voltages between the wires belonging to different phases, such as between a and c, or a and d. The phase voltages are $\sqrt{2}$ times larger than the mesh voltages, and are displaced from them in phase by 45 degrees. The proof of this is similar to that given for the three-wire two-phase system (Fig. 399).

The currents i_{1-2} flowing through the mesh are different from the

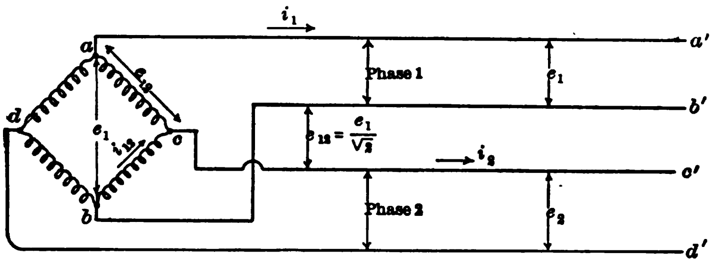


FIG. 403. Quarter-phase system, mesh connected.

line currents i_1 and i_2. As the power delivered to the line must be equal to that generated in the mesh, we have the relation

$$2i_1e_1 = 4i_{1-2}\,e_{1-2}.$$

Substituting in this equation $e_1 = e_{1-2}\sqrt{2}$, we obtain that $i_1 = i_{1-2}\sqrt{2}$, or the currents in the mesh are $\sqrt{2}$ smaller than the line currents. The phase angle between i_1 and i_{1-2} is 45 degrees, as only under these conditions does the difference of two equal vectors give a $\sqrt{2}$ times larger vector (See Fig. 399).

These relations are shown graphically in Fig. 404. The currents in the mesh are represented by the sides of the square *acbd*, the line currents by the diagonals *ab* and *cd*. With unbalanced load these diagonals are no longer equal or perpendicular to each other, and the square is distorted into a parallelogram $a_1c_1b_1d_1$. The voltages are represented in their magnitude and relative phase position by the square *ACBD* and its diagonals.

519. EXPERIMENT 25-D. — Electrical Relations in Quarter-Phase, Mesh-Connected System. — Connect an alternator in mesh, or, if this is not possible, have only the load mesh-connected. Balance up the currents in the four branches and read all the currents, voltages,

and watts. Unbalance the load and take again all the necessary readings for constructing the diagram shown in Fig. 404. Watts should be read as a check on the phase relations. With unbalanced load, line currents are no longer in phase with corresponding voltages, even though the load be non-inductive. Repeat the same experiment with inductive load, and compare watts measured on the line with those actually consumed in the four branches of the mesh.

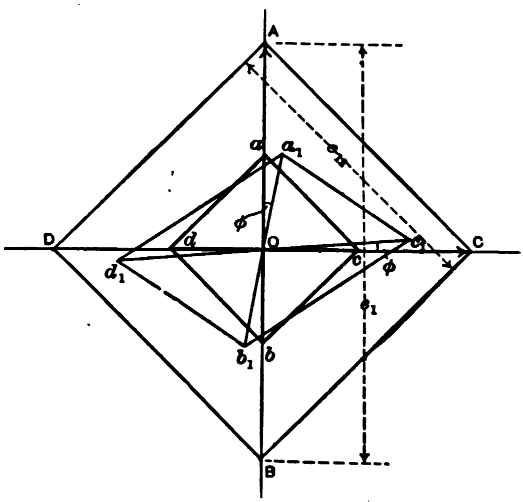


FIG. 404. Current and voltage relations in a quarter-phase system at a balanced and at an unbalanced load.

Report. Give the actual ratios of currents and voltages as found from the experiment. Select a few sets of readings at balanced and unbalanced load, and construct diagrams, as per Fig. 404, indicating both the currents and the voltages. Check the angles found by graphical construction with those calculated from the wattmeter readings.

THREE-PHASE SYSTEM.

520. A representation of the three-phase system is shown in Fig. 396; three alternating currents or voltages *a*, *b*, and *c*, relatively displaced by one third of a period, are there shown by sine waves and vectors. As in the case of the two-phase system (§ 511), various connections of generator windings are possible, all giving the same three-phase system on the line. The load may also be connected in two or three different ways.

Two schemes of three-phase connections are most commonly used: the star or *Y*-connection, shown in Fig. 405, and the Δ (delta) or triangle connection, Fig. 413. Both schemes are used in practice, and there are cases in which each kind of connections is preferable. The pros and cons of this question would hardly interest the student at this stage of his knowledge, and are therefore omitted. He should, however, become thoroughly familiar with the current, voltage, and power relations in both kinds of connections.

In some special cases the so-called V-connection (Fig. 416) is used, also the T-connection (Fig. 417). The electrical relations in all these connections are explained below.

521. Y-Connection — Current Relations. — Let OA, OB, and OC (Fig. 405) be three resistances connected in Y and constituting the load of a three-phase system. Let $O'A'$, $O'B'$, and $O'C'$ be the corresponding armature windings in which the three-phase currents are generated. The currents are relatively displaced by 120 degrees, as shown in Fig. 396. It may be seen at first that a fourth wire, such as ONO', is necessary as a common-return conductor for the phase currents. Experience and theory show, however, that this conductor may in most cases be dispensed with, since the sum of the three phase-currents is identically zero at all moments, at least when the load is balanced, and the currents vary exactly according to the sine law.

The easiest way to see this is to add point by point the ordinates of the three curves shown in Fig. 396. It will be found that their sum is equal to zero for any instant of time. This is a direct result of the mathematical proposition that the sum of sines of any three angles differing by 120 degrees is equal to zero. That is to say,

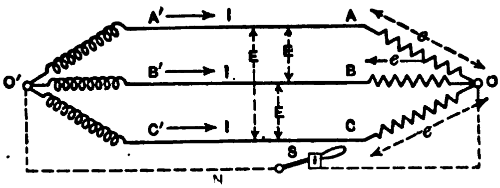


FIG. 405. Three-phase system, Y-connection. Positive directions are indicated by arrows.

$$\operatorname{Sin} x + \operatorname{Sin}\left(x + \tfrac{1}{3} \cdot 2\pi\right) + \operatorname{Sin}\left(x - \tfrac{1}{3} \cdot 2\pi\right) = 0.$$

To prove this formula, expand the terms; the result is

$$\operatorname{Sin} x + \operatorname{Sin} x \cdot \operatorname{Cos} \tfrac{1}{3} \cdot 2\pi + \operatorname{Cos} x \cdot \operatorname{Sin} \tfrac{1}{3} \cdot 2\pi$$
$$+ \operatorname{Sin} x \cdot \operatorname{Cos} \tfrac{1}{3} \cdot 2\pi - \operatorname{Cos} x \cdot \operatorname{Sin} \tfrac{1}{3} \cdot 2\pi;$$

or, after reduction,

$$\operatorname{Sin} x + 2 \operatorname{Sin} x \cdot \operatorname{Cos} \tfrac{1}{3} \cdot 2\pi.$$

But

$$\operatorname{Cos} \tfrac{1}{3} \cdot 2\pi = \operatorname{Cos} 120^\circ = -\frac{1}{2},$$

so that we finally get

$$\operatorname{Sin} x - \operatorname{Sin} x = 0,$$

which proves the formula given above.

The vectors of the three currents I_1, I_2, I_3 are shown in Fig. 406; the current in the return wire is a geometrical sum of the three. This

vector sum is evidently $= 0$, which is a graphical proof of the above proposition.

522. Y-Connection — Voltage Relations. — Two kinds of voltages are distinguished with the Y-connection; phase voltages e, such as between O and A, or O' and A', etc.; and line voltages E, such as AB, AC, and BC. Theory and experiment show that

$$E = e\sqrt{3}.$$

This is because the voltage between, say A and B, is a difference of the voltages OA and OB, or

$$= e \operatorname{Sin} x - e \operatorname{Sin}\left(x + \tfrac{1}{3}.\ 2\pi\right) = e\sqrt{3}.\ \operatorname{Sin}\left(x - 30 \text{ degrees}\right),$$

so that, apart from the phase displacement of 30 degrees, the amplitude of the voltage E between A and B is $\sqrt{3}$ times greater than that of e between A and the neutral point O.

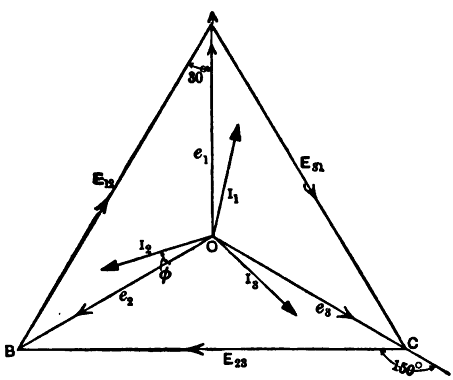


FIG. 406. Current and voltage relations in a Y-connected, three-phase system, at a balanced inductive load.

The same voltage relations are shown graphically in Fig. 406. The line voltages E are represented by the sides of the triangle ABC, the phase voltages e by the rays OA, OB, OC. The line voltages are relatively displaced by 120 degrees (note the arrow heads), as are the phase voltages. It will be seen directly from the diagram that the line voltages are $\sqrt{3}$ times larger than the phase voltages, and that the phase angle between the two is 30 degrees.

With balanced non-inductive load the vectors I_1, I_2, and I_3 of the line currents are in phase with the voltages OA, OB, and OC. With inductive load they are lagging behind by an angle ϕ, depending on the amount of inductance in the load.

The diagram shows that even with a non-inductive load the currents are not in phase with the voltages E across the line, but in phase with the voltages e between the corresponding lines and the neutral point.

523. Y-Connection — Unbalanced Load. — When the load becomes unbalanced, or currents do not vary exactly according to the sine wave,

equalizing currents flow through the return wire ONO', if such is provided. Otherwise, voltages and currents in the three line wires are considerably distorted. In practice, these currents never attain a magnitude sufficient to necessitate an extra conductor. All that is required is to have the points O and O' connected to the ground; the equalizing currents find their way through the ground.

The current in the return wire, or through the ground, is equal to the geometrical sum of the three line currents, as shown in Fig. 407. The load being unbalanced, the three vectors I_1, I_2, I_3 are shown of different lengths and at different angles to the corresponding voltages e_1, e_2, e_3. To find the geometric sum of the three currents, draw from the extremity of the vector I_1 the vector AB equal and parallel to I_2; from B draw the vector BC equal and parallel to I_3. The resultant vector OC, closing the polygon, represents the current I_n in the return wire, in its magnitude and phase position.

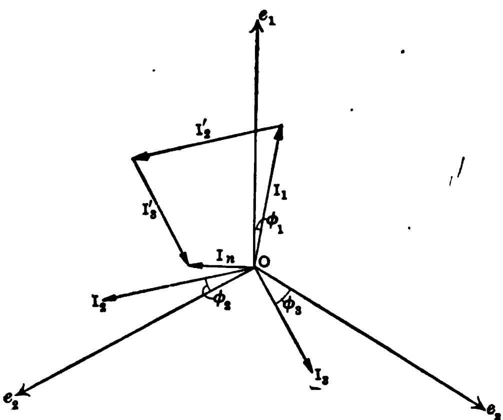


FIG. 407. Current and voltage relations in a Y-connected three-phase system with a low-resistance neutral connection (inductive load).

524. Influence of the Resistance of the Neutral Wire. — In some exceptional cases the resistance of the neutral wire may be quite considerable, or a poor ground connection may exist in the system. So long as the load is balanced, this may not be noticeable; but should the load become unbalanced, an appreciable difference of potential arises between the two neutral points O and O' (Fig. 405). This usually causes a further unbalancing of the voltages.

The electrical relations are indicated in Fig. 408. Let e_n be the voltage between the two neutral points O and O' (Fig. 408); the actual voltages at the terminals of the load are reduced (geometrically) by this amount. Subtracting e_n from the three generator voltages e_1, e_2, e_3, the three load voltages e_1', e_2', e_3' are obtained. If the load is non-inductive, the three currents I_1, I_2, I_3 are in phase with these voltages. Adding the three currents together, as in Fig. 407, the vector of the current in the common return wire is obtained. The relations shown in Fig. 408 correspond to the case of an infinitely large resistance of

the return circuit, for instance, when one of the neutrals is insulated from the ground. In this case the sum of the three currents must be $= 0$, because i_n is of necessity $= 0$.

525. Measuring Power in Y-Connection. — Total power W delivered to three resistances connected in Y (Fig. 405) is the sum of the watts developed in each phase, or $W = 3\,Ie$, where I and e designate the *effective* values. The neutral point is not always accessible, so that

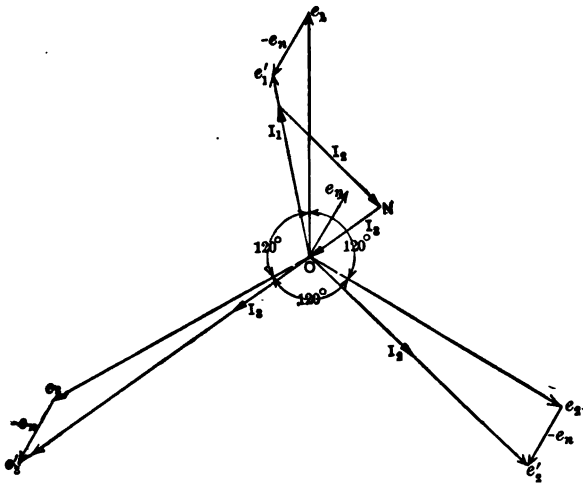


FIG. 408. Current and voltage relations in an unbalanced Y-connected system, with insulated neutral points.

the voltages e cannot always be measured. It is customary therefore to figure out the power in terms of the line voltage E. With the relation $E = e\sqrt{3}$ (Fig. 406) we get

$$W = EI\sqrt{3}.$$

If there is a phase displacement between the currents and the voltages e, due to some inductance in the load, the above expression must be multiplied, as in single-phase circuits, by Cos ϕ, and we have

$$W = EI\sqrt{3}\ .\ \text{Cos}\ \phi.$$

There are two ways of connecting wattmeters for measuring power in three-phase circuits: the three-wattmeter method (Fig. 409) and the two-wattmeter method (Fig. 410). The first method is self-evident: the power is measured in each phase separately and the results added together. This method gives correct results for total power under all circumstances, whether the load is balanced or not.

The two-wattmeter method is the one generally used in practice, since the neutral point O is not always accessible, also because with this method only two wattmeter readings are necessary, instead of three. This method is based on the fact that any of the three wires may be considered as a return wire for the currents flowing in two other wires. With the wattmeter connections, shown in Fig. 410, the wire B is taken as the return wire, so that the three-phase system is reduced to two single-phase systems A-B and C-B. The power in the first system is proportional to the current in A times the voltage between A and B. The power in the second is proportional to the current in C times the voltage between C and B. The wattmeters are connected so as to measure the power according to these expressions. The total power is equal to the sum of two simultaneous wattmeter readings, and the method is correct with balanced as well as with unbalanced loads.

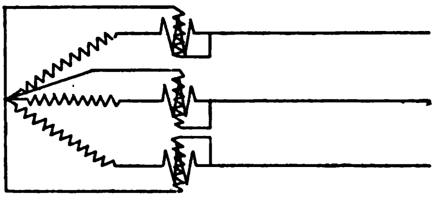


FIG. 409. The three-wattmeter method of measuring power.

526. Some Remarks on the Two-Wattmeter Method. — The following remarks may make the practical application of the method easier:

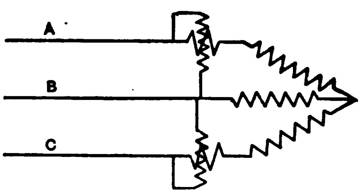


FIG. 410. The two-wattmeter method of measuring power.

(*a*) The two component readings are equal to each other only with balanced non-inductive loads; under all other conditions they are different (see § 527). When the power factor is below 50 per cent, one of the wattmeters begins to give negative deflections. If such is the case, either its current or voltage terminals must be reversed and a difference of the two readings taken, instead of their sum.

(*b*) It makes no difference which of the three wires is selected as the return wire: this affects only the component readings, but not the sum, which represents the total power in the system, and is always the same at a certain load.

(*c*) It is not always convenient to have two separate wattmeters and to read them simultaneously. Polyphase wattmeters are on the market for this purpose; they consist of two ordinary wattmeters with moving elements mounted on a common shaft, so that the indications

are automatically added together; the pointer indicates on the scale the total power. The connections are made as in Fig. 410.

(*d*) Where a polyphase wattmeter is not available, it is still possible to use one wattmeter instead of two, by having double-throw switches arranged so that this wattmeter can be switched over from one phase to the other (§ 49). Of course, this is permissible only when the load remains steady while the wattmeter connections are being changed.

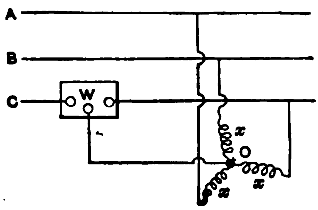


FIG. 411. Measuring power with an artificial neutral point (at balanced load).

(*e*) If the load is perfectly balanced, it is sufficient to measure the power in one phase only, as shown in Fig. 411, and to multiply the results by 3. It is assumed in Fig. 411 that the neutral point of the load is not accessible; therefore an *artificial* neutral point O is created by connecting three high resistances or inductances x in "Y" and connecting the potential winding of the wattmeter between one of the line wires and this neutral. If the neutral point of the generator or load is accessible, this complication is, of course, unnecessary.

(*f*) The two-wattmeter method should not be used when the neutrals are grounded and the load is unbalanced. In this case we actually

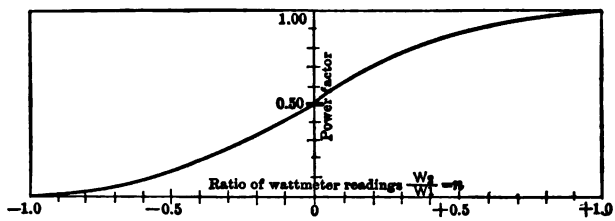


FIG. 412. The watt-ratio curve, for use with the two-wattmeter method.

have a four-wire system, so that three wattmeters are necessary for measuring total power. The ground connection serves as a common return conductor for the three other conductors.

527. Watt-Ratio Curve. — With the two-wattmeter method, two component readings are not equal to each other, when the load is inductive, though it may be balanced. The ratio of the two readings depends on the power factor of the load only, and not on its magnitude. A curve may be plotted (Fig. 412) showing the power factor of the load as a function of the ratio of wattmeter readings. This curve is some-

times useful in estimating the power factor, or as a check on the power factor figured from the ammeter, voltmeter, and wattmeter readings.

The equation of this curve may be derived as follows: Let the two wattmeters be connected as in Fig. 410; the first wattmeter measures the product (see Fig. 406)

$$W_1 = E_{1-2}I_1 \operatorname{Cos}(30° - \phi);$$

the second wattmeter registers

$$W_2 = -E_{2-3}I_3 \operatorname{Cos}(150° - \phi).$$

The minus sign is used in order to make the last expression positive; Cos $(150° - \phi)$ is in itself negative for small values of ϕ, while the wattmeter connections are such that with small ϕ (high power-factor) both readings are positive.

The second reading may also be represented identically by

$$W_2 = E_{2-3}I_3 \operatorname{Cos}(30° + \phi).$$

The ratio of the smaller to the larger reading, with balanced load, is

$$n = \frac{W_2}{W_1} = \frac{\operatorname{Cos}(30° + \phi)}{\operatorname{Cos}(30° - \phi)},$$

or, denoting the power factor Cos ϕ by f, we get, after some transformations,

$$n = \frac{W_2}{W_1} = \frac{f\sqrt{3} - \sqrt{1 - f^2}}{f\sqrt{3} + \sqrt{1 - f^2}}.$$

This is the equation of the curve shown in Fig. 412.

If it is desired to calculate the power factor from a given ratio of wattmeter readings, the above equation becomes

$$f = \operatorname{Cos}\phi = \frac{1}{\sqrt{1 + 3\left(\frac{1 - n}{1 + n}\right)^2}}.$$

The reading W_1 is always positive, when ϕ is positive (current lagging); W_2 is positive as long as ϕ is below 60 degrees. When $\phi = 60$ degrees, $W_2 = 0$, and the ratio $n = 0$; the power factor of the load $f = \operatorname{Cos}\phi = 50$ per cent. This is the point at which the ratio curve crosses the axis of ordinates.

With non-inductive load $W_1 = W_2$; $f = 1.00$, and $n = 1$. With purely inductive load $\phi = 90$ degrees, $W_1 = -W_2$; $n = -1$. Other points on the ratio curve are calculated in a similar way from the above given formula. It should be clearly understood that the ratio curve refers to *balanced* load only.

528. EXPERIMENT 25-E. — Electrical Relations in a Y-Connected System with Non-Inductive Load. — The purpose of the exercise is to make clear the relations derived in §§ 521 to 527. The measurements may be performed by connecting three resistances in Y to a three-phase supply. It is better, however, to have them connected to a small experimental alternator, the neutral point of which is accessible, so as to be able to investigate the effect of the common return wire.

It would be rather cumbersome to have an ammeter, a voltmeter, and a wattmeter for each phase; more than that, the results would not be directly comparable unless the instruments were in exact calibration. It is preferable, therefore, to use a "polyphase board" (§ 49) so arranged that the instruments can be connected in all three phases in succession, without opening the main circuit. With this device, one ammeter, one voltmeter and one wattmeter are sufficient for all polyphase measurements.

The experiment should be performed in the following order:

(1) *Balanced load.* Have the alternator Y-connected and load it on three resistances also Y-connected, as in Fig. 405. Adjust the resistances so as to have the same current in the three phases, and verify that:

(*a*) The sum of the three currents is identically zero. To prove this, insert an ammeter into the neutral wire; if the phases are well balanced the ammeter shows practically no deflection. Moreover, opening and closing the switch S in the neutral wire does not affect the ammeter readings in the three phases. (See Note I on p. 119.)

(*b*) There is no difference of potential between O and O', so that these points can be permanently grounded.

(*c*) Voltage E across the line is equal to $e\sqrt{3}$, where e is the phase voltage (Fig. 406).

(*d*) The power measured by the two-wattmeter method is the same as that determined by the three-wattmeter method; moreover, the result does not depend on which phase is selected as the return wire.

(2) *Unbalanced load.* Now unbalance the load; immediately a current will flow in the neutral, when the switch S is closed. Take readings with the switch S open and closed, and with the same load resistances. It will be seen that the neutral wire tends to keep the three phase voltages OA, OB, and OC equal. Without the neutral they are different, and there is also a difference of potential between O and O'. Introduce an appreciable resistance into the neutral wire, and observe its influence on the currents and voltages in the three phases.

In performing the experiment have before you the three diagrams (Figs. 406 to 408) and read all necessary data so as to be able to construct these diagrams. Have all the readings recorded systematically on a data sheet, such as shown below.

	Amperes.				Line Volts.			Phase Volts.			Watts (3-wattm. Meth).			Watts (2-wattm. Meth).		Total Watts.
	A	B	C	O	AB	BC	CA	AO	BO	CO	AO	BO	CO	A—AB	C—CB	
Inst. No.																
Const.																

Report. Give the actual ratios between the line voltages and the phase voltages, and compare them to the theoretical ratio $\sqrt{3}$. Plot curves showing the influence of unbalanced load in one phase on currents and voltages in the three phases, with and without the neutral wire. Select a set of readings at unbalanced load and construct a diagram as per Fig. 407. Construct a diagram for unbalanced load, without the neutral wire, as indicated in Fig. 408. Check the angles obtained by graphical construction with those calculated from wattmeter readings.

529. EXPERIMENT 25-F. — Electrical Relations in a Y-Connected System with Inductive Load. — This experiment supplements the preceding experiment. It is not necessary to repeat all the measurements made with the non-inductive load, but only those which offer new features with inductive load. Verify that two component readings in the two-wattmeter method are different even with a balanced load, when the load is inductive (§ 527). Measure, as a check, the same power according to the three-wattmeter method (Fig. 409). Take readings at various values of power factor in order to verify the theoretical equation of the watt-ratio curve (Fig. 412). Observe the fact that when the power factor is equal to 50 per cent, one of the wattmeters reads zero; when the power factor is reduced still further it becomes necessary to reverse the terminals and to take the difference of the two readings, in order to have the same power as indicated by the three-wattmeter method.

Connect an unbalanced load, with and without the neutral wire, and

take all the readings necessary for constructing the diagrams shown in Figs. 407 and 408.

Report. Give, in the form of curves, or of a table, the values of power measured by the two-wattmeter and the three-wattmeter methods. Plot the theoretical watt-ratio curve and the curve actually observed. Construct typical vector diagrams for balanced and unbalanced load.

530. Delta-Connection — Current and Voltage Relations. — The connections are shown diagrammatically in Fig. 413; Fig. 414 shows the

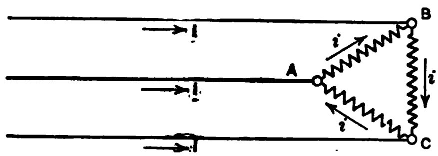


FIG. 413. Three-phase system, " delta "-connection.

same connections when each phase is loaded separately, for instance when the load consists of incandescent lamps. Electrically the schemes shown in Figs. 413 and 414 are equivalent. Delta-connection differs

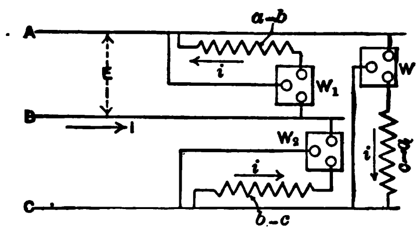


FIG. 414. A three-phase system loaded in " delta."

from the Y-connection in that it has no neutral point, and the phase load is subjected to the full line pressure E. On the other hand, with Y-connection each phase consumes the full line current I, while in a delta-connected load the current i in each phase is only $I \div \sqrt{3}$ of the line current I. This can be proved in exactly the same way as it was proven before that $E = e\sqrt{3}$: namely, with the positive directions of the currents shown in Fig. 345 we have, that the current I in the line wire A is a difference of the currents i in AB and AC. This difference is

$$i \operatorname{Sin} x - i \operatorname{Sin} (x + \tfrac{1}{3} \cdot 2\pi) = \sqrt{3} \cdot i \operatorname{Sin} (x - 30°)$$

so that, apart from the phase difference of 30 degrees, the current $I = i\sqrt{3}$.

The same relations are shown graphically in Fig. 415. The three line voltages E are represented by the sides of the triangle ABC. The currents in the load, Bk, Bl, Bm, are in phase with these voltages, provided the load is non-inductive. The line currents are represented by the sides of the triangle klm. They are in phase with the fictitious Y-voltages OA, OB, and OC (compare Fig. 406). It will be seen from the figure that the line currents are $\sqrt{3}$ times larger than the load currents, and that the phase difference between the two is 30 degrees. The same result is obtained above graphically.

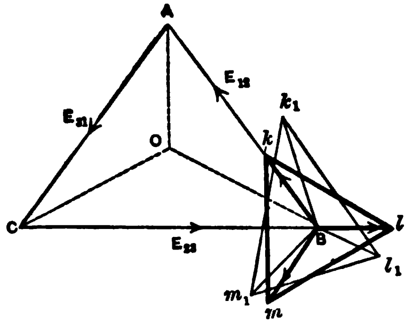


FIG. 415. Current and voltage relations in a "delta"-connected three-phase system at a balanced and at an unbalanced load.

When the load in the three phases is different (unbalanced load), though non-inductive, the currents Bk, Bl, Bm are still in phase with the corresponding voltages constituting the triangle ABC. However, the vectors of the currents being of different lengths, klm is no more an isosceles triangle. For the case of an inductive load see Note II on page 119.

531. Delta-Connection — Power Relations. — The three-wattmeter method in application to the delta-connection is shown in Fig. 414, the power being measured separately in each phase of the load. The *two-wattmeter* method (Fig. 410) is the one commonly used in practice. In fact, *when the two-wattmeter method is used, it is not necessary to know in which way the load is connected, since one of the line wires can always be assumed to be a return wire for the other two line wires.* The single-wattmeter method, as shown in Fig. 411, can also be used equally well, provided, of course, that the load is balanced in all three phases, as in the case of three-phase motors.

The power delivered by an alternator is the same whether the load is connected in Y or in delta, provided that the line voltage and the line currents are the same in both cases. With the Y-connection, each phase consumes a current I at a pressure $e = E \div \sqrt{3}$, or a power equal to $IE \div \sqrt{3}$. With the delta-connection each phase consumes a current $I \div \sqrt{3}$ at a voltage E, or again the same power $IE \div \sqrt{3}$. The total power W in the three phases is also the same in both cases and is equal to $3 \times EI \div \sqrt{3}$, or $EI \cdot \sqrt{3}$, as is proved above.

532. EXPERIMENT 20-G. — Electrical Relations in a Delta-Connected System at Non-Inductive Load. — The purpose of the experiment is to make clear the numerical relations deduced in §§ 530 and 531. Connect three non-inductive resistances as per Fig. 414, and adjust them so as to have the same current in the three phases. The generator, used as the source of power, may be either Y- or delta-connected, since the relations are studied on the load only. As a matter of fact, no special alternator is required, and the load may be connected to the laboratory power supply. Use a data sheet similar to the one shown in § 528. Make the following measurements:

(*a*) Measure the ratio between the currents in the line and in the delta, and see how close they check with the theoretical ratio $\sqrt{3}$.

(*b*) See if the power measured by the three-wattmeter method, as per Fig. 414, checks with that measured by the two-wattmeter method, as per Fig. 410. Make this comparison with balanced and with unbalanced load.

(*c*) Gradually unbalance the load in one of the phases, first increasing it and then reducing it below that in the other two phases. Note the effect on the currents, voltages, and phase relations in all three phases and in the line.

(*d*) Open the circuit in one of the phases of the load and compare the resulting voltages and currents with those at balanced load.

(*e*) Select an unbalanced load and take all the readings necessary for constructing the diagram shown in Fig. 415. Measure watts in order to be able to check the phase angles.

Report. Figure out the ratio between the line currents and the load currents; compare it with the theoretical ratio $\sqrt{3}$. Give the results of comparison of the two-wattmeter and the three-wattmeter methods. Plot curves showing the effect of underloading or overloading a phase; use amperes in the unbalanced phase as abscissæ. State your findings when one of the phases was opened. Construct a diagram, as in Fig. 415, for a balanced and for an unbalanced load.

533. EXPERIMENT 25-H. — Electrical Relations in Delta Connection at Inductive Load. — The experiment supplements the one preceding. It is not necessary to repeat all the measurements specified there, but only those which offer some difference with inductive load, in particular the runs (*b*), (*c*), and (*e*).

534. V-Connection. — The three-phase combination shown in Fig. 416 is known as the V-connection. BA and BC represent the secondary windings of two transformers, or two generator windings. The load

is connected as usual, either in Y or in delta. The V-connection is obtained from the delta-connection by omitting the generator or transformer winding between A and C, thus compelling the two other phases to take up the whole of the load. With three windings, each carries one third of the load; with V-connection each winding carries one half of the load.

If, for instance, the total load is 300 kw., three 100-kw. transformers are required with Y- or delta-connection, and two 173-kw. transformers with V-connection.* The total cost of the latter is less, and this is the advantage of the V-connection over the delta scheme. In large power houses, transformers are sometimes connected in delta, and, should one of them be disabled, the two others temporarily carry the load in V, possibly being loaded above their rated capacity.

It should be clearly understood that only generator, transformer, and motor windings may be connected in V, and not ordinary ohmic

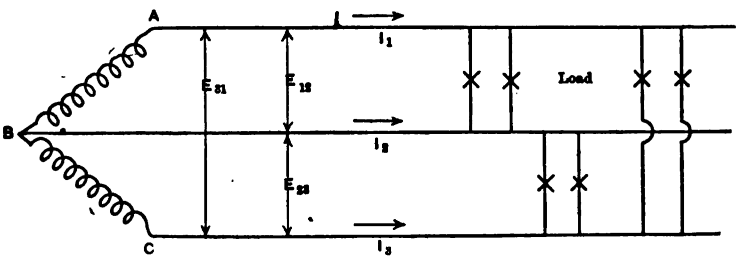


FIG. 416. Three-phase system, V-connection.

or inductive resistances. This is because the load in the three phases remains constant only with the proper phase relation between the e.m.f.'s induced in AB and BC. This condition is fulfilled in generators and motors, the windings in the two phases being suitably spaced relative to each other. It is also fulfilled in transformers, because they transmit phase relations, practically without distorting them.

It may seem at first that the increase in current in the windings AB and BC, after the winding AC has been removed, should be $50 - 33\frac{1}{3} = 16\frac{2}{3}$ per cent. A little consideration will show, however, that the current increases $\sqrt{3}$ times, because the additional current, which the windings have to carry, is out of phase with their former currents,

* Using two transformers instead of three brings in a phase displacement of Cos $30° = \sqrt{3}/2$, so that the apparent output of each transformer becomes 173 kw., instead of 150 kw. See explanation above.

For, assuming the line currents to be I in both cases, the currents in the transformer windings are also necessarily equal to I with V-connection, as may be clearly seen from Fig. 416. With delta-connection, the currents in the transformer windings are equal to $I \div \sqrt{3}$ (see § 530).

The increase in the currents being greater than the increase in the power to be delivered by each transformer, the currents in V-connected transformers must be out of phase with the voltages, even at non-inductive load. One way to prove this is as follows: total power with balanced load is $EI\sqrt{3}$; hence, each of the windings has to supply $EI\sqrt{3} \div 2$. The voltage at the terminals of each winding is E, and the current flowing through it is I; therefore the phase displacement ϕ between the two must be such that $\cos\phi = \sqrt{3} \div 2$, in order that the power may be represented by the above expression. The angle ϕ corresponding to the above cosine is 30 degrees.

The same relations may be deduced from Fig. 415. When the transformer winding AC is taken out, its current Bm must be carried in series by the two other transformers. The transformer AB has to carry its own current Bk and the current Bm, the sum of the two being km. In the same way the current in the transformer BC is changed from Bl to ml. It will be seen that the currents are thus increased $\sqrt{3}$ times, and a phase displacement of 30 degrees is produced.

It follows from the above that the power in a V-connected system cannot be determined by merely taking volts times amperes in the two transformers, even with a non-inductive load. The power should in all cases be measured by the two-wattmeter method, as in Fig. 410.

535. EXPERIMENT 25-I. — Electrical Relations in a V-Connected System. — The purpose of the experiment is to afford practice in connecting transformers in V, and to make clear the numerical relations explained in the preceding article. Unless a special V-connected generator is available (see footnote to § 510), the connections should be established through two transformers, whose primaries are connected in V to the source of supply, and the secondaries are connected in V to the load. It is well to have a third transformer in order to observe the difference between the delta and the V-connection.

(*a*) Apply a balanced non-inductive load and measure currents and voltages with the transformers in delta and in V. Use a wattmeter to prove the phase difference of 30 degrees spoken of in the preceding

article. Unbalance the load, and take all the readings necessary for constructing a vector diagram of current and voltage relations.

(*b*) Unbalance the load in the phase *AB* or in the phase *BC* by a certain per cent and measure the resulting unbalancing in currents and in watts supplied by each transformer. Now unbalance the phase *AC* *by the same amount*, and again measure amperes and watts in both transformers. The practical significance of this experiment is this: In some cases two *V*-connected transformers supply a balanced load of three-phase induction motors, and it is desired to connect to the same supply some single-phase lighting. The question to decide is, whether the lighting should be connected to the phase *AC*, where the unbalancing would be taken up by both transformers, or to one of the other phases where it would affect one of the transformers more than the other.

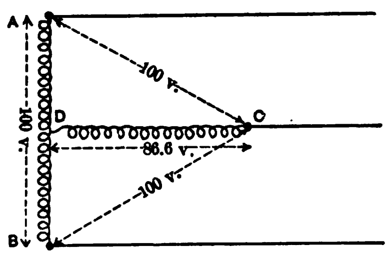


FIG. 417. Three-phase system, T-connection.

(*c*) Apply a balanced inductive load and investigate the relation between the power factor of the load and the phase angle between the currents and the voltages in the transformers themselves. It will be found, that this angle, which was equal 30 degrees at non-inductive load, increases for one transformer and decreases for the other, as the load becomes more inductive. This shows that at non-inductive load the current is lagging in one transformer, and is leading in the other.

Report. Give the diagram of connections used; figure per cent increase in currents with the change from delta- to *V*-connection. Determine the actual phase displacement in the transformers, and show how it varies when the load becomes inductive. Give an explanation of this on the basis of the diagram, Fig. 415. Give your findings in regard to unbalanced load, and corroborate them by a vector diagram.

536. T-Connection.— Besides *V*-connection there is another way of producing three-phase currents with two windings only; this is the *T*-connection shown in Fig. 417. The two windings there shown represent either the secondary windings of two transformers or two phases of a special generator. The three-phase line is connected at *A*, *B*, *C*, the voltages being the same (100 volts) between any two wires. The voltage induced in the winding *DC* is de-phased 90 degrees against the voltage induced in *AB*, as shown in Fig. 418. But the voltage across

AC, being a geometrical sum of DC and of one half AB, has a phase displacement of 120 degrees from AB. The number of turns in the winding DC is

$$\sqrt{3} \div 2 = 86.6 \text{ per cent}$$

of that in AB. The reason for this may be seen from Fig. 418, because only under such conditions ABC is an equilateral triangle.

The line currents with balanced load are represented by the vectors I_1, I_2, and I_3; the former two are displaced by 30 degrees from the voltage AB. Thus, with T-connection the currents in the transformer AB are 30 degrees out of phase with the voltage induced in the transformer, with non-inductive balanced load. One of the currents is leading the e.m.f., the other is lagging behind it. Therefore, when the load becomes inductive, the phase angle increases in one half of the transformer and decreases in the other half. The current I_3 is in phase with the voltage DC at non-inductive load.

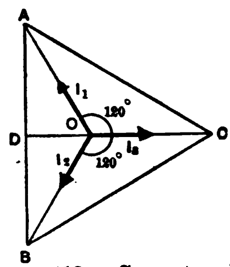


FIG. 418. Current and voltage relations with T-connection.

The power delivered to the line is measured, as usual, by the two-wattmeter method. The following is a check calculation showing that the total power W in two T-connected transformers is equal to $IE\sqrt{3}$, as with the other three-phase connections. Taking the three currents (Fig. 418), and multiplying them by the corresponding voltages and values of the power factor, we have:

$$W = DA \,.\, I_1 \,.\, \text{Cos } 30° + DB \,.\, I_2 \,.\, \text{Cos } 30° + DC \,.\, I_3 \quad ;$$

$$W = \frac{E}{2} \,.\, I \,.\, \frac{\sqrt{3}}{2} + \frac{E}{2} \,.\, I \,.\, \frac{\sqrt{3}}{2} + \frac{E\sqrt{3}}{2} \,.\, I;$$

or

$$W = EI\sqrt{3},$$

which was to be proved. Each transformer carries one half of the total power.

537. EXPERIMENT 25-J. — Electrical Relations in a T-Connected System. — The purpose of the experiment is to illustrate the electrical relations explained in the preceding article. If a T-connected generator is not available, take two transformers, connect their primary and secondary windings in T, and then connect them to the supply and to the load respectively. One of the transformers must have a tap D

(Fig. 417) in the center of each winding, the other transformer must have a lower number of turns (86.6 per cent). In practice, both transformers are made identical, and both are provided with taps at 50 per cent and 86.6 per cent of their windings, so as to be interchangeable.

(*a*) Measure, at no load, all the voltages shown in Fig. 418. If the transformer *DC* has additional taps, investigate the effect of the magnitude of voltage *DC* on the line voltages *AB*, *BC* and *CA*.

(*b*) Provide a balanced non-inductive load, measure currents, voltages and the power in both halves of the transformer *AB*, in order to check the theoretical phase difference of 30 degrees. Gradually introduce some inductance into the load and repeat the same measurements; it will be found, that the phase difference decreases in one transformer and increases in the other. It will also be found, that the line voltages become somewhat unsymmetrical, because the drop of voltage in the two halves of the transformer is different with leading and lagging currents. In order to reduce this unbalancing, the coils on the halves *AD* and *BD* are interposed to bring them into a closer inductive relation.

(*c*) Unbalance the load, first in the phase *AB*, and then in the phase *AC* by the same per cent; measure currents and power in the two transformers in order to determine in which case the unbalancing affects the system less.

Report the results and show in how far they corroborate the theory. Construct vector diagrams of current and voltage relations (Fig. 418).

538. Determination of Size of Conductors in Polyphase Lines.— The relations in polyphase circuits being somewhat more complicated than in ordinary direct-current and single-phase circuits, the beginner sometimes encounters difficulties in understanding these relations, particularly in application to the most important practical question with which an operating engineer is most likely to deal, viz., figuring the size of conductors for a two-phase or a three-phase transmission line. The necessary explanation as to how a three phase or two-phase line can be reduced to an equivalent single-phase line and calculated as such is given in § 455. A numerical example may be of use here, in showing that polyphase lines can also be figured out directly from the relations derived above.

The problem usually presents itself in some such form as this: 500 kw. are to be transmitted by means of a three-phase system, over a distance of 4 miles, with a loss of 8 per cent of the power delivered; the pressure at the receiving end of the line is to be 6600 volts. What is the size of conductors to be used?

Let us first assume the load to be non-inductive; the current in each wire is then, according to the formula $W = EI \cdot \sqrt{3}$,

$$I = \frac{500}{6.6 \times \sqrt{3}} = 43.8 \text{ amp.*}$$

The loss of power allowed in the line is $0.08 \times 500 = 40$ kilowatts, or $40{,}000 \div 3 = 13{,}333$ watts in each wire. The resistance R of each wire is determined from the equation $I^2R = 13{,}333$, from which $R = 6.95$ ohms. Resistances are usually given in wire tables per 1000 feet of conductor; the resistance of our wire per 1000 feet must be

$$\frac{6.95}{4 \times 5.28} = 0.329 \text{ ohm,}$$

which corresponds approximately to No. 5 Brown & Sharp gauge.

If the load is inductive, the power factor being, say, 80 per cent, a heavier wire is required, because it takes a larger current to transmit the same power at a lower power factor. As the loss in the line is proportional to the square of the current, the resistance per 1000 feet now has to be $0.329 \times (0.80)^2 = 0.210$ ohm; this corresponds to about No. 3 B. & S. wire.

If the transmission is to be effected by means of the two-phase four-wire system the size of the wire is figured out as follows: With 500 kw. transmitted by two phases, each phase transmits 250 kw., so that the line can be calculated as a single-phase line of the same voltage, transmitting 250 kw. The current at non-inductive load is $250 \div 6.6 =$ about 38 amperes, and the resistance of the line

$$R = \frac{0.08 \times 250{,}000}{38^2} = 13.9 \text{ ohms.}$$

This gives

$$\frac{13.9}{5.28 \times 4 \times 2} = 0.329 \text{ ohm per 1000 feet,}$$

or the same size of wire, as figured above for the three-phase system. This shows that there is a saving of 25 per cent in copper with the three-wire system as compared to the two-phase system, because, the size of the wire being the same in both cases, there is one wire less with the three-phase system.

PHASE TRANSFORMATION.

539. There are cases in which it is desirable to transform two-phase power into three-phase power, or vice versa. Thus, for example, power is sometimes generated by means of two-phase alternators, then the

* The power being given in *kilowatts*, it is convenient to measure the pressure in *kilovolts:* 6600 volts = 6.6 kilovolts.

voltage is raised, the system being simultaneously transformed into a three-phase system for transmission and distribution. The advantage of this arrangement is that only three line wires are required instead of four. On the contrary, in some cases two-phase local distribution is preferred, especially for lighting, where each phase is used separately; the three-phase supply is then converted into a two-phase four-wire combination. These transformations are usually accomplished by means of the so-called Scott system described below.

540. The Scott Two-Phase to Three-Phase Transformation.—A *T*-connection is used with this system on the three-phase side (Fig. 419); the other windings of the transformers are connected directly to the two-phase supply. In *T*-connection (Fig. 417), as well as in the

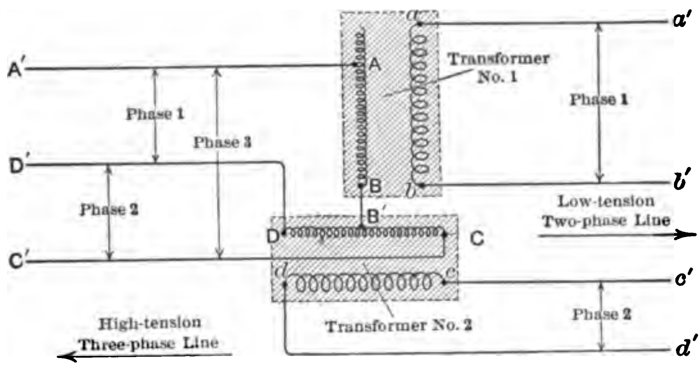


FIG. 419. The Scott two-phase to three-phase transformation.

ordinary two-phase connection (Fig. 397), the two voltages generated in the windings are displaced in phase by 90 degrees. The only difference is that in the two-phase system the two windings *ab* and *cd* are used independently, while in the *T*-connection the corresponding windings are interconnected at *B*, and the three-phase line is connected to the three remaining terminals *A*, *C*, and *D*. Moreover, in the two-phase system, both windings have the same number of turns, while on the three-phase side the winding *AB* must have only 86.6 per cent of the turns of *CD* in order to produce an equilateral triangle of voltages (compare Fig. 418).

541. EXPERIMENT 25-K.—The Scott System of Polyphase Transformation.—Connect two transformers, as per Fig. 419, one side to the source of supply, the other side to the load. Use a polyphase board (§ 49) so as to be able to measure currents, voltages, and watts on the three-phase side and on the two-phase side. Connect first a balanced

non-inductive load, and take all the readings necessary for determining the actual phase relations of voltages and currents. Unbalance the load on one side, and see how it affects the supply; do this with all the phases, because the system is not symmetrical. Perform a similar test with an inductive load; note in all cases the unbalancing of voltages resulting from an internal drop in the transformers.

Report. Give the connections actually used, the ratios found with inductive and non-inductive load; explain by means of vector diagrams the results obtained.

542. Six-Phase System. — It is mentioned in § 586, that the copper loss in the armature of a rotary converter decreases with the increase in the number of slip-rings, because the alternating currents are more evenly distributed in the armature. As the heating in the armature determines the output and the rating of the rotary converter, it becomes advantageous with large rotaries to increase the number of slip-rings to six. It would be out of the question to have six-phase currents generated and transmitted to rotary substations. This is, however, not necessary, as six-phase currents can be easily produced in the substation itself, from the two-phase or three-phase currents delivered from the power house, as is explained below.

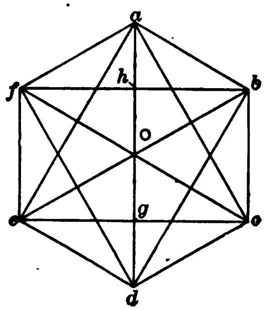


FIG. 420. A diagram illustrating the practical methods of transformation from two- or three-phase to six-phase.

Similarly to the three-phase and quarter-phase systems, either star or mesh connection may be used with the six-phase system (Fig. 420). The star voltages are represented by the rays *Oa, Ob, Oc,* etc. The mesh voltages are *ab, bc, cd,* etc. It will be seen that in this case star voltages are numerically equal to mesh voltages, because *Oab, Obc,* etc., are all equilateral triangles.

543. Three-Phase to Six-Phase Transformation. — The transformation is based on the fact that in a six-phase system three of the phases may be considered as merely three other phases reversed. Thus, with a star connection, the voltage *Of* is the reversed *Oc,* etc. With the mesh connection the voltage *ab* is the reversed voltage *de,* etc.

Fig. 421 shows three transformers whose secondaries are wound in two sections each; the primaries of the transformers, not shown in the figure, are connected in *Y* or delta to the three-phase supply. The two terminals of each section are marked by *s* (start) and *f* (finish). To get a star-connected six-phase combination, connect together all

the terminals marked *s*; this gives the neutral point *O*; the terminals *f* are connected to the six slip-rings of the rotary, in the order 1, 2, 3, etc., as indicated.

If the mesh connection is desired, the finish of coil 1 is connected to the start of coil 2, finish of coil 2 to start of coil 3, etc.

The above-described combination of transformer windings is not the only one possible for converting three-phase into six-phase currents. As a general proposition, there are as many separate methods of transformation as there are possible combinations for connecting the six vertices, *a*, *b*, *c*, *d*, *e*, *f* (Fig. 420), with lines of three directions. This last limitation is necessary because there are but three voltages to begin with, and the phases may be only reversed, but not shifted by a certain angle.

These combinations are as follows:

(1) Connecting *a* to *b*, *b* to *c*, etc.

(2) Connecting the vertices to the point *O*.

(3) Connecting them by three diagonals, *ad*, *be*, *cf*.

(4) Connecting by two deltas, *aec* and *fbd*.

The first two methods are explained in Fig. 421; the method (3) does not require double secondaries; the method (4) may be obtained by properly connecting the double secondaries, shown in Fig. 421.

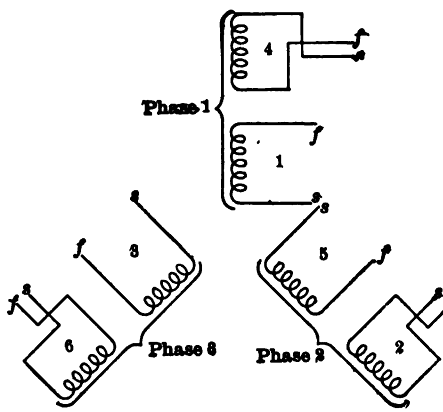


FIG. 421. Transformation from three-phase to six-phase by means of three transformers, each with two secondary windings.

By using the *V*- or the *T*-connection, it is possible to convert a three-phase system into a six-phase system using two transformers only; thus,

(5) By using two *V*'s, *eac* and *fbd*.

(6) By using two *T*'s, *ecga* and *fbhd*.

The primaries of the two transformers are connected in *V* or *T* respectively; the secondaries are wound in two sections, the four windings being connected in double *T* or double *V*.

544. Two-Phase to Six-Phase Transformation. — This transformation may be understood directly from the method (6) mentioned in the previous article, only the primaries of the two transformers,

instead of being connected in T, are connected each across one phase of the supply, as in the Scott system (Fig. 419).

545. EXPERIMENT 25-L. — Six-Phase Transformation. — The purpose of the experiment is to verify experimentally the relations derived in §§ 543 and 544. At least two transformers must be available, or preferably three, in order to be able to try all the six combinations mentioned above. The transformers should be provided, if possible, with double secondary windings and suitable taps on the primary windings, for obtaining identical secondary voltages with different connections.

Combinations (1) and (2) can be tried on open circuit; the other combinations may be investigated on a closed circuit only, because otherwise not all of the six vertices of the hexagon are interconnected. For instance, with method (4) there is no electrical connection between the points a, e, c on one hand, and f, b, d on the other hand; this connection is established through the load only.

A regular six-phase rotary converter is the most natural load for this experiment; if such is not available, an experimental rotary, such as is shown in Fig. 438, will answer the purpose, since it will interconnect the phases in at least one point. If no rotary is available, the system may be interlinked by producing an artificial neutral point O connected to the six vertices by equal resistances or inductances, connected in star.

Report. Give the actual electrical connections used during the test and the voltages observed. Plot the observed voltages graphically, as a vector diagram, and compare the theoretical ratios, shown in Fig. 420, with those actually observed.

546. Transformation from a Polyphase to Single-Phase System. — It is sometimes desirable to connect a single-phase load to a three-phase supply, *without unbalancing the phases.* Such a transformation is physically impossible, without bringing into play a revolving device which can store electrical energy at a certain part of an alternation, and deliver it again at another time. The reason for this is, that the energy delivered by a three-phase alternator is constant at all times, while that taken by a single-phase load fluctuates between a certain maximum and zero, or even becomes negative, if the load is inductive. With a revolving motor-generator set, interposed between the alternator and the load, the difference between the energy delivered by the three-phase system and that taken in by the load is stored as a part of the momentum of the revolving part of the set, to be delivered at the next moments. The motor-generator is dispensed with if an unbalancing of the polyphase system is not objectionable. Thus, on

single-phase railways, two tracks, or various sections of the same track, are supplied from different phases of the same polyphase alternator, the load being at times out of balance.

The inverse transformation from a single-phase to a perfect polyphase system is, for the same reason, impossible without the medium of a revolving motor-generator set. An imperfect two-phase system (split-phase arrangement) can be produced by suitable combinations of resistance, inductance, and capacity. See §§ 81 and 348.

NOTE I TO PAGE 104. When the form of the induced e.m.f. differs considerably from the true sine wave, the current and voltage relations are different from those deduced above. With grounded neutrals the current in the ground wire is sometimes of an appreciable magnitude, in spite of a perfectly balanced load. When the neutrals are insulated from each other the voltage between them is quite different from zero at balanced load (oscillating neutral). Should the student have a difficulty of this kind, he is advised to substitute inductances for resistances as a load. Inductive coils offer a comparatively large reactive resistance to higher harmonics of the currents, thus reducing their magnitude. Therefore, the simple theoretical relations are approximated much more closely than with non-inductive resistances.

NOTE II TO PAGE 107. With a balanced inductive load, the triangle klm (Fig. 415) is isosceles, but is displaced by an angle ϕ from the position shown in figure. With an unbalanced inductive load the triangle of currents is distorted into the shape $k_1l_1m_1$. The load currents are no longer equal to each other, nor in phase with the corresponding voltages. However, the relation that each I is a geometric difference of the two adjacent i's holds true in all cases.

CHAPTER XXVI.

THE SYNCHRONOUS MOTOR — OPERATING FEATURES.

547. It has been pointed out in § 331 [under (7)] that an alternator may act under certain circumstances as a motor, and is called in this case a *synchronous* motor. The action of such a motor may be explained as follows: Suppose the machine to be single-phase and to be brought up to the required speed by some external means. Assume that at a certain moment the relative position of the pole-pieces and of the armature winding is such that the winding attracts the pole-pieces (Fig. 249). As the machine is supposed to revolve synchronously, the pole-pieces change their position during one alternation of the supply current by one pole pitch, so that the north poles come in place of the south poles, and vice versa. At the same time the direction of the armature current is reversed, so that the mutual force between the two is again attraction and not repulsion.

Another explanation limited to the case of polyphase synchronous motors is that the polyphase armature winding produces a revolving field (see § 332) which rotates synchronously in the air-gap. The field poles of the machine must revolve at the same speed in order that there be a constant attraction between the two magnetic fields; otherwise south poles and north poles are brought together in succession and the resultant attractions and repulsions neutralize each other.

548. Starting Synchronous Motors. — The above given explanation of the action of the synchronous motor shows that it must be started and brought up to full speed before being capable of carrying a load. The following means are used for starting synchronous motors:

(1) A small induction motor, usually mounted on the same shaft with the synchronous motor, or geared to it.

(2) If a source of direct current is available, the exciter machine belted or direct-connected to the motor, is used for starting.

(3) Synchronous motor itself (if polyphase) is converted into an induction motor and started as such.

For further details see § 587 on starting rotary converters. Synchronizing is accomplished as explained in §§ 328 and 329 in application to alternators.

549. EXPERIMENT 26-A. — Exercises in Starting Synchronous Motors. — See directions for starting rotary converters in § 588.

Note in particular the precaution mentioned there in regard to a high voltage induced in the field winding at the start.

550. EXPERIMENT 26-B. — Synchronous Motor Brake Test. — The purpose of the experiment is to investigate the performance of a synchronous motor, mainly in regard to its efficiency and power factor under various loads. The experiment is performed similarly to the brake test on induction motor (§ 342), except that the measurement of slip is omitted, the speed being synchronous.

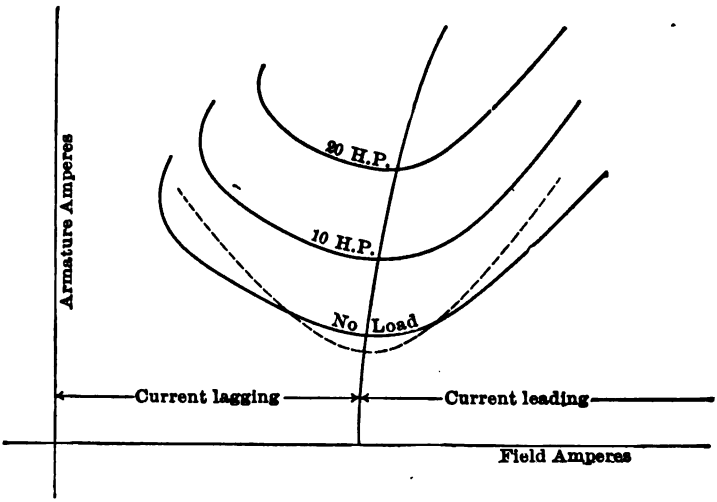


Fig. 422. Curves showing the influence of varying excitation on the armature current in a synchronous motor (*V*-curves or phase characteristics).

The power factor of the motor may be varied within wide limits by regulating the field current, but, since the field current in actual operation is usually kept constant, the brake test should be performed with a certain definite (constant) value of the excitation.

Set the field current so as to have a power factor of 100 per cent at full load, and keep it constant throughout the test. In some cases synchronous motors are over-excited to draw leading currents from the line, in order to improve the power factor of the plant. Take another set of curves with the field current adjusted so as to have, at full load, a power factor of 90 to 80 per cent with leading current.

Report. Plot performance curves similar to those shown in Fig. 271, except the curves of speed and slip.

551. Influence of Excitation on Power Factor. — Experience shows that when a synchronous motor is carrying a certain load its field current may be varied within comparatively wide limits without throwing the motor out of step. The armature current which the motor takes varies with different values of excitation, as shown in Fig. 422.

With a certain value of field current, the armature current is a minimum, and the power factor is 100 per cent. Reducing the field current increases the armature current, and draws current from the line, having a lagging component. Increasing the excitation also increases the armature current, but makes it leading instead of lagging. Beyond certain limits of excitation, the motor falls out of step. Because of their shape the curves shown in Fig. 422 are sometimes called *V*-curves. They are also known as the *phase characteristics* of the synchronous motor.

One explanation is offered by considering the effect of the armature reaction, as in § 320, under (1). Let the field current be adjusted so that the motor takes a current in phase with the applied e.m.f., this current producing a certain reaction on the motor field. Increasing the field current makes the counter-e.m.f. of the motor too high for the load. This causes a leading component to be taken from the line, that reduces the field flux to its former value, or thereabouts. Conversely, when the exciting current is reduced below normal, the motor takes in a lagging wattless component, which strengthens the field and again establishes the conditions necessary for carrying the load. Another explanation, based upon the action of the armature inductance, and similar to explanation (2) in § 320, is given in the next article.

552. Vector Diagram of the Synchronous Motor. — The vector diagram, shown in Fig. 423, explains the shape of the *V*-curves. OE is the vector of the applied voltage at the terminals of the motor, and is assumed to be constant. This voltage is partly balanced by the induced counter-e.m.f., EA_1 of the motor, partly absorbed by the impedance drop OA_1 in the motor armature. Let Oi_1 be the current taken by the motor and lagging behind the voltage OE by an angle ϕ. The vector OA_1 may be constructed as a resultant of the vectors of ohmic and inductive drop. But the ohmic drop is usually small as compared to the inductive drop, and the total drop may usually be assumed to consist of the inductive drop only. The vector of this drop is, as usual, perpendicular to the direction of the current producing the drop.

Increasing the excitation increases the counter-e.m.f. EA_1 induced in the armature; at a certain value of the field current the triangle EA_1O is converted into EA_2O. The vector of the armature current, being perpendicular to OA_2, now assumes the position Oi_2, and is

leading, instead of being lagging, as before. The currents Oi_1 and Oi_2 are so drawn in the diagram that their working component Oi, in phase with the line voltage, is the same; this is because the output, or the load, being the same in both cases, the true input is also essentially the same. By adjusting the excitation so as to have a counter-e.m.f. equal to EA, the total current is reduced to Oi, in phase with the applied voltage; this corresponds to the lowest points on the V-curves (Fig. 422). The vector diagram shows that either reducing or increasing the field current beyond this value increases the armature current.

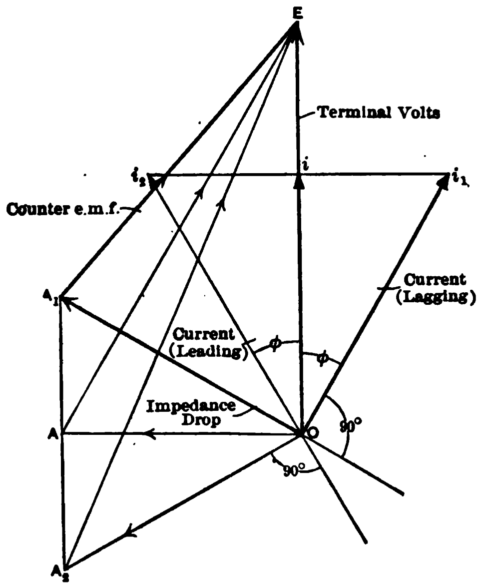


Fig. 423. Vector diagram of a synchronous motor.

The shape of V-curves depends upon the inductive drop OA in the armature: increasing OA, or the inductance, makes the curves more flat; reducing it tends to make the curves sharper, as shown by the dotted line.

The foregoing explanation considers the effect of the armature inductance only, while that given in § 551 is limited to the armature reaction. A correct theory which takes both factors into account is outside the scope of the present book.

A motor with flat V-curves is more stable in operation than one with sharper V-curves, because in the former case fluctuations in the armature current and the resulting equalizing currents are less pronounced.

In some cases choke coils are connected in series with the line to increase the inductive drop and to make the motor more stable with varying load, or with a fluctuating frequency of the supply (see also § 599).

553. EXPERIMENT 26-C. — Determination of V-Curves of a Synchronous Motor. — The theory and the significance of *V*-curves is explained in §§ 551 and 552 above. The general arrangement of the experiment is similar to the brake test (§ 550). (*a*) Put on quite a heavy load, and adjust the excitation so as to have a power factor of 100 per cent. Gradually *reduce* the field current, keeping the same load, until the motor falls out of step. Be sure to have a reliable circuit-breaker which will instantly open the circuit, preventing the motor from being short-circuited. Read armature volts, amperes, and watts; also field current, brake load, and speed. (*b*) Start the motor again, adjust the excitation as before, and gradually *increase* the field current to the practicable upper limit; take same readings as above. (*c*) Repeat similar runs with lighter loads; also take a run at no load. (*d*) Finally take a no-load saturation curve as in § 318, running the machine as generator.

For this experiment it is better to have a calibrated generator, or a transmission dynamometer (§ 254), than to use an ordinary Prony brake, because the motor has to be started and stopped several times. If no provision can be made for measuring the output, *V*-curves may be taken for constant input, as shown on the wattmeter. This is the case illustrated in Fig. 423, the working component of the current being constant.

Report. Give the connections used during the test. Plot the *V*-curves and the corresponding values of power factor to field current as abscissæ; also plot the saturation curve at no-load. Construct a few triangles, such as OEA_1 (Fig. 423), from the test data. In constructing the diagram use the values of power factor from the *V*-curves, and take from the no-load saturation curve the values of counter-e.m.f. which correspond to certain values of the field current. The values of the impedance drop OA may be thus determined; dividing them by the corresponding armature currents will give the impedance of the armature. See if this impedance comes out the same from all the tests. No particular accuracy can be expected in this determination, because the diagram is but an approximate one, the armature reaction not being taken into account (see § 551).

554. Hunting of Alternators and of Synchronous Motors. — The phenomenon of hunting is the same as described in § 599 in application to rotary converters; the methods used for its prevention are also

practically the same as are described there. A type of dampers used with revolving field machines for preventing hunting is shown in Fig. 424. The dampers consist of heavy copper wedges driven in between

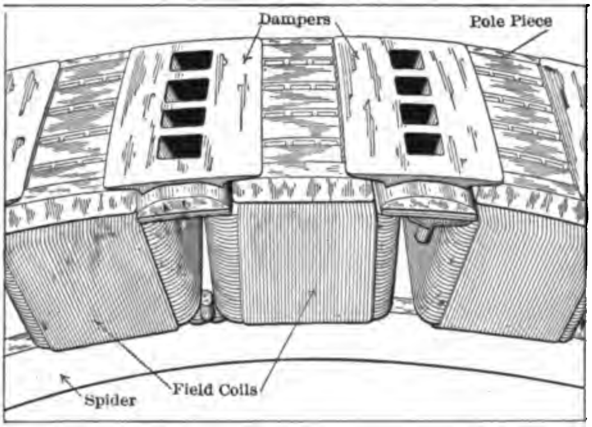


Fig. 424. Copper bridges (dampers) between the poles of an alternator or a synchronous motor, to prevent hunting.

the tips of the pole-pieces. A more recent construction is shown in Fig. 442. Metal collars on field coils serve the same purpose.

FREQUENCY METERS.

555. Instead of measuring speed of alternators by speed indicators, or tachometers, it is convenient to have an instrument which reads directly in cycles or alternations, and may be placed on the switchboard at any distance from the machine. Such instruments are called *frequency meters*, and are often found in large generating stations and substations. The type largely used in this country is based on a purely electrical split-phase arrangement. Another type, popular in Europe, utilizes vibrating reeds attuned to different frequencies. These two types of frequency meters are described in the following articles.

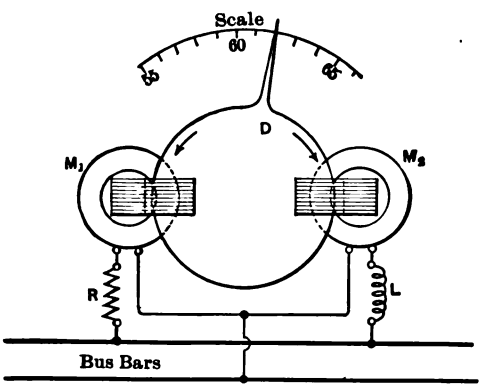


FIG. 425 An induction-type frequency meter (Westinghouse).

556. Split-Phase Frequency Meter. — The frequency meter shown in Fig. 425 is essentially a combination of two induction voltmeters described in § 42. Two split-phase electromagnets M_1 and M_2 are each of the same construction as the one shown in Fig. 43. They act in opposite directions on the aluminum disk D, thus constituting a differential voltmeter. To make the instrument respond to changes of frequency, the winding of one of the electromagnets is connected in series with some inductance L, and the other winding with some resistance R. The current in the branch M_1 containing the resistance is practically independent of frequency; the current in the branch

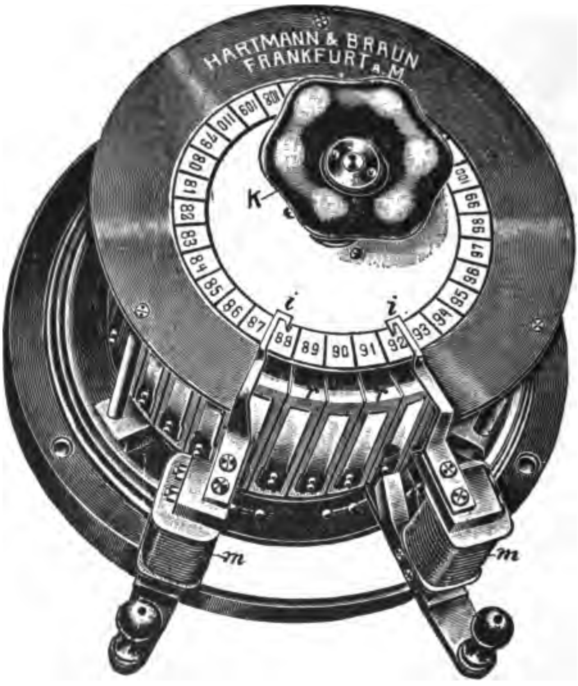


FIG. 426. Hartman & Braun electro-acoustic frequency meter.

M_2 decreases as the frequency increases, thus giving preponderance to the electromagnet M_1. To each frequency there corresponds a definite position of the aluminum disk, and the instrument is calibrated in cycles per second. The calibration is made by connecting the frequency meter to an alternator, the speed of which is measured directly by a speed counter.

557. Resonance or Vibrating Reed Frequency Meter. — The frequency meter shown in Fig. 426 is based on an entirely different

principle, namely, on that of vibrating steel reeds. A steel strip, Fig. 427, fastened at one end and free at the other end has a natural vibration period, and is easily set into vibrations by outside impulses of the right frequency. The reeds are made of different length and different inertia, so as to vibrate at different frequencies, and are mounted in a circle. By means of the handle the reeds may be brought in succession before the poles of two laminated electromagnets shown in front. These electromagnets are connected to the alternating-current supply, the frequency of which it is desired to measure. When one of the electromagnets is opposite the correct reed it vibrates violently producing a distinct tone; the corresponding frequency is read on the scale.

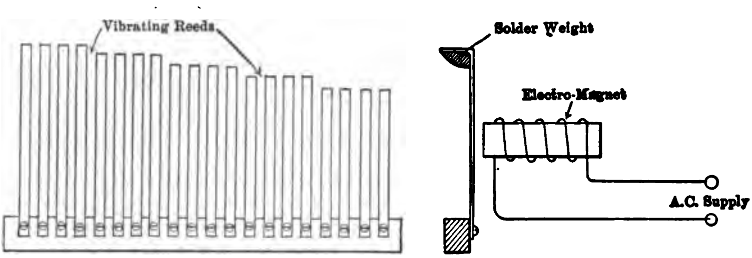


FIG. 427. Measuring frequency of alternating current by means of vibrating steel reeds.

The two electromagnets are at first set close to each other, so as to act on the same reed; then, when the proper reed has been located, the magnets are separated so as to inclose three or five reeds with the right reed in the center. This practically stops its vibration, and the sound which would be annoying, while deviations from the standard frequency may be noted on the adjacent reeds.

It has been found that the reeds may be made to vibrate by currents of double their normal frequency if direct current be allowed to flow at the same time through separate windings on the cores of the electromagnets, thus polarizing the reeds in one direction. This doubles the useful range of the instrument. The explanation is, that a non-polarized reed is attracted by the current of either direction, while a polarized one is attracted by impulses of one direction only, being repelled by the opposite impulses. Consequently, a double of the original frequency of current is required to make the reed vibrate at its natural frequency.

Frequency meters, built on the same principle for switchboard service, have electromagnets extending over all the reeds. The vibrating reed is observed on the dial, instead of being noted acoustically. This makes the instrument direct-reading without the necessity of turning

the knob. The same principle is applied to tachometers intended to be read at a distance. An interrupter is belted or direct-connected to the shaft, the speed of which is to be measured, and a battery is connected to the frequency indicator, through the interrupter. The number of interruptions or vibrations depends on the speed of the shaft, and the instrument may be calibrated in revolutions per minute, or in any other desired units.

CHAPTER XXVII.

ALTERNATORS AND SYNCHRONOUS MOTORS — COMMERCIAL TESTS.

558. THREE important points in the performance of alternators with respect to which certain guarantees are usually made in contracts of sale are efficiency, temperature rise, and per cent regulation.

These guarantees are usually expressed about as follows:

(1) The efficiency of the machine shall not be less than . . . . per cent at full load, not less than . . . . per cent at three-quarters load, etc.

(2) Temperature rise, under definitely specified conditions of operation, shall not be more than . . . . degrees Centigrade.

(3) Regulation, or voltage drop between no load and full load, shall be within . . . . per cent.

In many cases it is out of the question to test large alternators in actual operation, especially before they leave the factory. Various test methods have been devised for checking the above three points, without expenditure of much power. The most important of these tests are described below.

EFFICIENCY.

559. The efficiency of alternators and synchronous motors is determined in practice by the same two methods as is the efficiency of direct-current machines, viz., from the losses (Chapter XIII) and from an opposition run (Chapter XIV). For general information concerning efficiency and losses see §§ 272 to 275; most of the explanations given there for direct-current machines are applicable, with self-evident changes, to alternating-current machines. Here, also, iron loss and friction are determined by either of the three methods used with direct-current machines, namely: (*a*) the machine is driven mechanically by a small auxiliary motor; (*b*) the machine is driven electrically as synchronous motor; (*c*) by the retardation method. The first of these methods is the one most used in testing alternators.

560. EXPERIMENT 27-A. — Efficiency of an Alternator from Losses. — For this test, drive the machine by a small motor at the rated speed, with various values of exciting current, and note the input

into the driving motor. Finally take off the belt and determine the losses in the driving motor itself. For details, see the conclusion of § 275.

Measure the resistances of the field and of the armature by the drop-of-potential method. Before leaving the laboratory, ascertain the rated field current at full load, or assume it with sufficient margin above that at no load, unless an actual load test can be performed.

In machines wound with heavy conductors, not sufficiently subdivided, copper loss in the armature is considerably increased by eddy currents in these conductors. In such cases it is well to determine the actual copper loss in the armature from the so-called short-circuit test. The armature winding is short-circuited through suitable ammeters, and the machine is driven at the rated speed, with such an excitation as to give the full rated current in the armature. The iron loss is negligible, the field being very weak, so that the input into the driving motor corresponds to the copper loss and friction in the alternator. The friction is determined separately by driving the machine without excitation, and the copper loss in the armature calculated as the difference of the two.

Report. Show actual connections used, and describe the performance of the test. Plot an efficiency curve for non-inductive load, and also plot separate losses to kilowatts output as abscissæ. The excitation loss is usually calculated from the formula i^2r, where i is the exciting current and r the resistance of the field winding. This is not quite correct; the loss in the field rheostat must also be charged to the machine, because it constitutes an unavoidable loss of energy, and is present in every alternator. It is more correct, therefore, to figure out this loss by the formula ei, where e is the standard voltage of the direct-current supply, or of the exciter. Another way is to figure out the efficiency of the alternator without the excitation loss, and to state kilowatt loss in the field separately.

561. EXPERIMENT 27-B. — Efficiency of an Alternator from the Air-Box Test. — All the losses taking place in electric machines are finally converted into heat. This gives a method for determining the sum total of the losses by measuring the quantity of heat (in thermal units) developed in a machine during a certain period of time. The machine under test is inclosed in an air-tight box with walls made of poor conductors of heat, and is run under such conditions as to have all the losses present to their full value. A definite quantity of air per minute is blown through the box, and its temperature measured at the intake and at the exhaust. After a certain number of hours of

run, the temperature of the machine becomes constant, all the heat developed being conveyed away by the air. Knowing the rate of air discharge, and the difference of temperature, the thermal units developed may be calculated from the specific heat of air. Converting them into watts (see § 726) gives the total losses of the machine.

The difference of temperatures of the air is usually quite small and must be measured very accurately. Sensitive electrical thermometers with an accuracy of at least 1/10 of a degree are well adapted for the purpose. The air-box method has been applied in a few cases for acceptance tests of very large alternators, in power houses where it was not possible to check the guaranteed efficiency by any other method.

The experiment can be arranged so that it will not be necessary to know the absolute quantity of air supplied by the blower. For this purpose the machine is stopped, and a *known* amount of power is supplied within the box, for instance, by passing a current through the armature windings, from the outside. The blower must continue to run at the same rate as during the regular test. From the difference of temperatures after steady conditions have been established, the total loss in the machine can be calculated. Let, for instance, the difference in temperature during the load test be 10 degrees C., while it was only 5 degrees C. when 2500 watts were delivered to the armature from outside. Evidently the total loss in the machine was

$$2500 \times \frac{10}{5} = 5000 \text{ watts.}$$

562. Efficiency from an Opposition Run. — Two alternators may be tested for efficiency under actual load conditions without expenditure of much power by loading them in opposition (Chapter XIV). Thus, two identical machines may be driven at full load by a small auxiliary motor, as is explained in § 300 in application to direct-current machines. The machines must be rigidly coupled together so as to preserve the same frequency and the same phase relation throughout the test. An ammeter, a voltmeter and a wattmeter are connected between the machines. One machine acts as a generator, the other as a motor. Any desired load, at practically unity power factor, may be obtained by varying the relative angular position of the armatures, by means of the coupling. Leading or lagging components are added by varying the field excitation of one of the machines.

Let the input into the auxiliary driving motor (corrected for the losses in the motor itself) be w, and the wattmeter reading be W. The efficiency of both machines may be assumed to be the same; let it

be $= \eta$. The electrical power produced by the machine acting as generator is converted into mechanical power in the machine acting as motor, and is delivered back to the generator through the shaft and the coupling. The driving motor merely supplies the losses of the set.

Expressing these relations mathematically, we have: the input into the synchronous motor being W, its mechanical output, delivered to the shaft is ηW; in addition to this the auxiliary motor supplies to the shaft an amount of power $= w$. Thus the power available for driving the generator is $\eta W + w$. The efficiency of the generator being η, its electrical output is $\eta\ (\eta W + w)$; on the other hand, we know from the wattmeter reading that the output of the generator is W. Thus we have the condition

$$\eta\ (\eta\, W + w) = W.$$

This is a quadratic equation with respect to η; the positive solution is

$$\eta = -\frac{\frac{1}{2}\, w}{W} + \sqrt{\left(\frac{\frac{1}{2}\, w}{W}\right)^2 + 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

With the aid of this formula the efficiency of either machine may be calculated from the observed values of W and w. The copper loss in the field must be taken into account separately.

563. Behrend's Split-Field Test. — As two identical machines are not always available, Mr. B. A. Behrend proposed (after a suggestion by Mr. W. M. Mordey) to connect two halves of the same alternator in opposition to each other, using one half as generator, and the other as synchronous motor. The connections, in application to a three-phase machine, are shown in Fig. 428. The armature winding is short-circuited through three ammeters; the field winding is divided into two halves, connected in opposition, and each provided with a regulating rheostat. The same scheme is shown more in detail in Fig. 429. In order to conduct the current to the middle point of the field winding, an extra slip ring c is provided, in addition to two regular slip rings a and b. Or, else, the middle point of the winding is simply connected to the spider, and a temporary brush is mounted on one of the bearings, so as to make a contact with the shaft of the machine. The current in each half of the field is regulated independently by the rheostats R_1 and R_2, and ammeters A_1 and A_2. Only two ammeters are used in the armature circuit, because, if the currents in the two phases are equal, the third current is necessarily the same, the three vectors forming an equilateral triangle.

When the currents in the two halves of the field are equal, no currents flow in the armature winding, the e.m.f.'s induced in two halves of the

armature being equal and opposite. This corresponds to the case of two identical machines coupled in opposition and excited to the same degree. By weakening the current in one half of the field winding, the two e.m.f.'s induced in the armature are unbalanced, and a current flows through the ammeters *AA*. The machine does not deliver any useful output, so that the input into the driving motor is merely sufficient to cover the losses in the machine itself. By having the same armature current and the same field current (on the strongest side) as at full load, the input into the driving motor represents the sum total of the losses in the alternator under test. The copper loss in the field must be

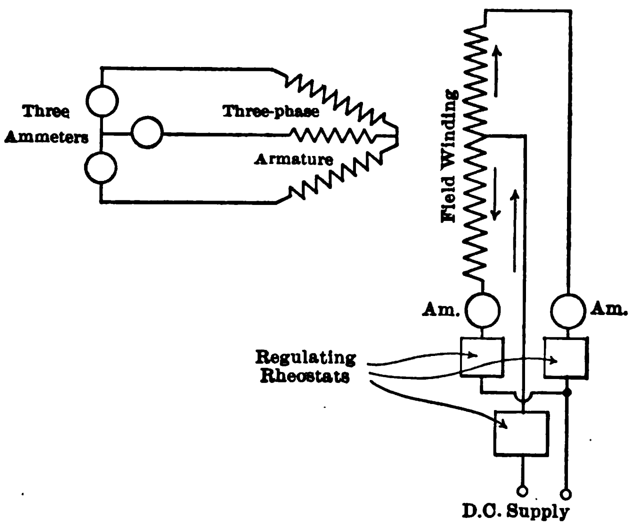


FIG. 428. Diagram of Behrend's split-field method for testing alternators.

calculated separately, since the exciting current is supplied from an independent source.

In order to determine the proper value of the exciting current on the " generator " side of the machine, the voltage is measured across one set of the armature coils, by puncturing the insulation with sharp points on the voltmeter leads. Suppose, for instance, that the machine under test is a 2200-volt, 150-ampere, 24-pole, 3-phase, *Y*-connected alternator. The voltage between each terminal and the neutral point is $= 2200 \div \sqrt{3} = 1271$ volts. A 24-pole machine has 12 groups of armature coils per phase (see Fig. 246); thus, the voltage across one set of coils is $1271 \div 12 = 105.9$ volts. The two rheostats, R_1 and R_2, must be adjusted so as to produce 150 amperes in the ammeters *AA*,

and 105.9 volts across a set of armature coils. Then the losses in the machine are the same as under actual load conditions.

An objection may be raised, that iron loss is smaller than under actual load conditions, only one half of the poles having the required field strength. Mr. Behrend proved, however, by direct tests that the core loss determined from a no-load run is practically the same as with the split-field test.

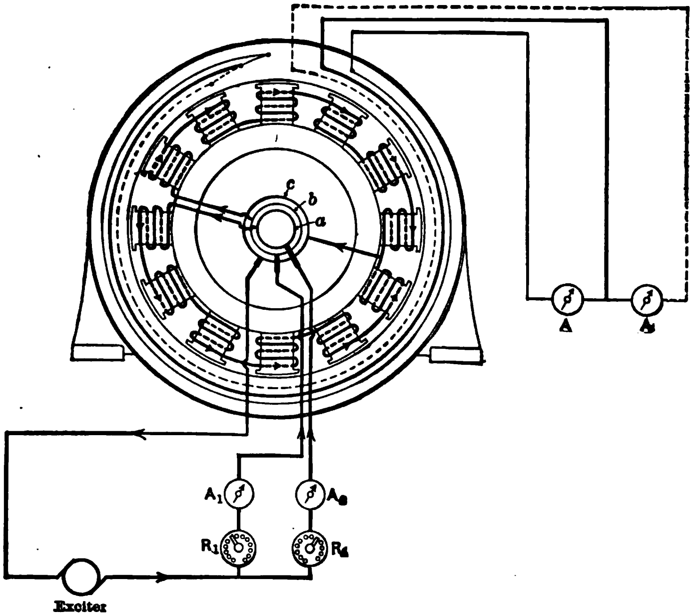


FIG. 429. Connections for Behrend's split-field test on a three-phase alternator.

If the corrected input into the driving motor is w, and the rated output of the machine is W,

$$\text{Efficiency} = \frac{W}{W + w + \text{field } i^2r}$$

Behrend's method is limited to alternators with a considerable number of poles, not less than eight or ten. Evidently, with the field connections, shown in Fig. 429, there are two adjacent north poles and two adjacent south poles, which cause an irregularity in the induced e.m.f. With a considerable number of poles this irregularity does not seriously affect the results.

564. EXPERIMENT 27-C. — Efficiency of an Alternator from an Opposition Test. — The experiment is performed either on two identical machines, as explained in § 562, or by using the split-field

arrangement shown in Fig. 429. Take readings on partial loads, at full load, and also on an overload, so as to be able to plot a complete efficiency curve. It is well to determine the losses separately, as in § 560, so as to check the efficiency from the losses.

TEMPERATURE RISE.

565. The rise of temperature, due to the losses, is of importance in four parts of the machine:

(1) Armature windings.

(2) Armature core.

(3) Field winding.

(4) Collector rings.

The temperature rise in the two latter parts depends on field current only, and may be determined by running the machine a certain number of hours with the field fully excited, and the armature circuit closed or open, as the case may be. The temperature of the collector rings is measured by thermometers; that of the field coils by thermometers, as well as by the increase in resistance. For copper, resistance increases by 0.42 per cent for each degree Centigrade (see § 5).

It is more difficult to obtain the correct conditions for temperature rise in the armature, because of an exchange of heat between the core and the winding. For this reason, both copper and iron must be brought up to the temperatures during the test, which they are supposed to have during the actual operation. This means, that a full-load current must be flowing through the armature windings, and at the same time a normal flux maintained in the core. Several methods have been proposed for obtaining these conditions without the expenditure of power, corresponding to full-load output. Some of them are described below, and their limitations indicated.

566. Separate Heat Runs for Copper Loss and Core Loss.—When machines of a standard type, on which heat runs have been previously made, are tested, the purpose of the temperature test is chiefly to ascertain if the new machine may be expected to give the same temperature rise in actual operation, as the machines previously tested. In this case it is permissible to run the machine first on open circuit for iron loss only, and then with the armature short-circuited for copper loss alone. If the temperature rise under these conditions is not more than with the machines previously built, which proved satisfactory in operation, the test is considered as conclusive.

Of course, such a run is satisfactory for the manufacturer, but not for the customer; a modification described in the next article makes it possible to approach much more closely the actual temperature rise.

567. Hobart and Punga's Temperature Test. — With this method the machine under test is run *alternately* on iron loss and on copper loss so as to get the same *average* amount of losses converted into heat in the armature, as under actual load conditions. An example may serve to illustrate this method: Suppose the armature copper loss in an alternator to be equal to 20 kw. and iron loss 36 kw. The machine is run, say, 10 minutes with the armature short-circuited and with such a current flowing through it as to give 60 kw. loss. Then the machine is run 20 minutes on open circuit with a field excitation such that it gives an iron loss equal to 54 kw.; after this it is run again on copper loss, etc. Under such conditions the same *total* amount of heat is supplied to the machine as if 20 + 36 kw. were supplied continually. Indeed, 60 kw. supplied ⅓ of the time are equivalent to 20 kw. supplied all the time, and 54 kw. converted into heat ⅔ of the time are the same as 36 kw. supplied continuously. At the end of several hours the machine reaches the same temperature as if these losses were supplied simultaneously all the time, with the advantage that only a small amount of energy is necessary when either iron or copper loss is supplied alone.

This method implies a knowledge of the magnitude of iron loss; the same may be determined by driving the machine at no load, first excited, and then with the field circuit open. The difference of input into the driving motor gives the iron loss of the alternator.

In order to save time and power, it is advisable to heat up the machine by an overload, viz., by running it for a time with higher armature currents and higher field excitation than are calculated for the heat run. When the machine is warmed up, the copper loss and the iron loss are reduced to their correct values. With this method the machine assumes its final temperature in a much shorter time than it would otherwise.

Temperature rise in the field winding with this test may not be the same as in regular operation. When the machine is running on iron loss, the field is above normal, while it is considerably below normal during the periods of run for copper loss. It is possible, however, to so adjust the relative duration of the two parts of the run and the values of the losses, that the *total* amount of heat developed in the field winding will be the same, as under actual load conditions. For details of the necessary calculations, see the original paper in the *Electrical World*, 1905, Vol. 45, p. 759; the method is also explained in Hay's *Alternating Currents*, p. 175.

568. Heating the Armature with Direct Current. — It may seem at first that the most natural way to conduct the heat run on an alter-

nator would be to run it with full field on iron loss, and at the same time send a direct current through the armature windings, to produce the required copper loss. There are, however, two great objections to this method:

(1) The armature must be so connected that the total induced A. C. voltage will be equal to zero; otherwise a short-circuit would be produced through the source of direct current.

(2) The stationary field produced by the direct current in the armature windings should not induce high e.m.f.'s in the field winding.

With a single-phase machine, direct current may be sent through two halves of the armature winding connected in opposition; a three-phase machine may be temporarily connected in delta, and direct current introduced by opening one of the vertices of the delta. There are also some other combinations possible, with the use of transformers, etc., but, as a matter of fact, this method is very little used in practice.

569. Heat Run by Opposition. — If a second alternator of suitable size is available, the machine under test may be run in connection with the other machine used as a synchronous motor. By under-exciting a synchronous motor, it may be made to take a large apparent input with a comparatively small expenditure of power. The arrangement is similar to that described in § 562, except that in this case it is not necessary to have the two machines rigidly coupled together.

Instead of using two separate machines, the two halves of the machine under test may be connected in opposition, as in Fig. 429, and an adjustment of currents and voltages made, as explained in § 563. The machine runs with the same copper loss and the same iron loss as under actual load, and gives therefore the correct temperature rise. This method gives satisfactory results only when the number of poles is not less than eight; hence, unfortunately, it cannot be used with modern high-speed turbo-generators.

570. Critical Comparison of the above Methods. — When only approximate results are required, or the test is merely a check to compare the machine with machines previously built, separate heat runs for copper loss and iron loss (§ 566) are sufficient.

For machines with a sufficient number of poles, Behrend's opposition test (§ 569) seems to be the most practical.

Turbo-generators may either be loaded on synchronous motors (§ 569) or heated by the Hobart and Punga method (§ 567).

With the advent of the steam-turbine, large manufacturing companies began to provide facilities on their testing floors for running sets up to several thousand kilowatt under actual load conditions. In some cases, an artificial load for temperature run is provided in power

houses, where the machines are installed. Whenever possible, temperature run should be performed on the machine actually loaded, because this permits the determination simultaneously of the regulation of the machine, and the testing of its mechanical features, such as heating of bearings, vibration, etc.

571. EXPERIMENT 27-D. — Heat Run on Alternators. — The purpose of the experiment is to make practical application of the methods described in §§ 566 to 569, rather than to obtain actual numerical data on temperature rise. A regular temperature run takes at least six hours, and with large machines even ten or twelve, while the methods themselves may be illustrated in a considerably shorter time. It is therefore recommended that the student connect up the machine under test, and run it for a few minutes according to the various methods described above, merely to make clear to himself the connections and the operation.

After this, select one of the methods, say Hobart and Punga's, or Behrend's, and run the machine for an hour or two. Take regular temperature readings by thermometers every five or ten minutes, and check them from time to time by the increase in resistance. Select an overload such as to obtain a considerable temperature rise in the comparatively short time allotted for the experiment.

Report. Give the actual connections used, the readings obtained with various methods, and plot heat curves as far as the run was carried. If desired, extrapolate the heat curves by the method described in § 493.

VOLTAGE REGULATION.

572. The meaning of the term "regulation" is explained in § 319; the physical significance of the three factors affecting regulation is given in § 320. These factors, in the order of their importance, are:

(1) Armature reaction.

(2) Armature inductance.

(3) Ohmic drop.

It has also been shown that regulation and voltage drop depend on power factor of the load, as well as on the value of the current. The methods by which regulation of alternators can be determined from actual tests, or predetermined by calculation, are described below.

573. Regulation at Power-Factor Zero. — According to the accepted definition of regulation, it refers to the variation of the terminal voltage at a power factor of 100 per cent. In testing machines, however, and for purposes of investigation, it is much more convenient

to consider voltage drop and regulation at the power factor zero. The reasons are as follows:

(1) In many cases it is easier to obtain a large load current at a power factor practically equal to zero than at 100 per cent or thereabout. Moreover, the regulation varies considerably at high values of power factor, but is practically constant at any value of power factor, say below 20 per cent. This may be seen by consulting Figs. 253 and 256.

(2) The drop at a power factor zero is the largest possible, and is therefore more acceptable as a measure of the quality of the machine. Besides, in calculating regulation at other values of power factor on the basis of an observed regulation at zero power factor, less error is committed than by beginning with the regulation at the power factor of 100 per cent and figuring out from it the regulation at other values of power factor.

(3) The theory of armature interference is much simpler at a power factor zero, because the armature winding produces only a demagnetizing but no distorting action on the field (Fig. 250).

In view of the above considerations, there is a tendency on the part of some progressive engineers to introduce into contracts and into general engineering practice *regulation at a power factor zero as a standard,* instead of regulation at the power factor of 100 per cent used at present.

Regulation at power factor zero may be conveniently represented by two curves, NV and OV_0 (Fig. 430). The former gives the values of the terminal voltage to field current as abscissæ, with a full-load current, lagging 90 degrees, flowing through the armature. On the other hand, the curve OV_0 gives terminal voltage at no load. If gA is the rated voltage of the machine, the regulation at the power factor zero is represented by the per cent ratio A_0A to gA. The curve NV may be obtained experimentally by loading the machine on an under-excited synchronous motor, on induction motors running light, on choke coils, etc.

The method for *predetermining* the regulation at other values of power factor, from the regulation observed experimentally at a power factor zero, is explained in §§ 582 and 583 below.

574. EXPERIMENT 27-E. — Regulation of an Alternator from a Synchronous Motor Load. — The experiment is performed as in § 322, but the power factor of the load (synchronous motor) is kept always below 20 per cent. It is important to have a synchronous motor of sufficient size, so as to obtain enough points on the curve NV (Fig. 430). Begin with the heaviest current which the generator can carry

and with the highest voltage possible at this load with a low power factor. The load is adjusted by regulating the field current of the synchronous motor. Gradually reduce the excitation of both machines, so as to get a curve similar to NV. Take another curve for a smaller value of the armature current, etc. Finally take the no-load saturation curve OV_0.

No exact wattmeter readings are required, except that the power factor must be sufficiently low; actual experience shows, that when the power factor is below 20 per cent, terminal voltage is practically

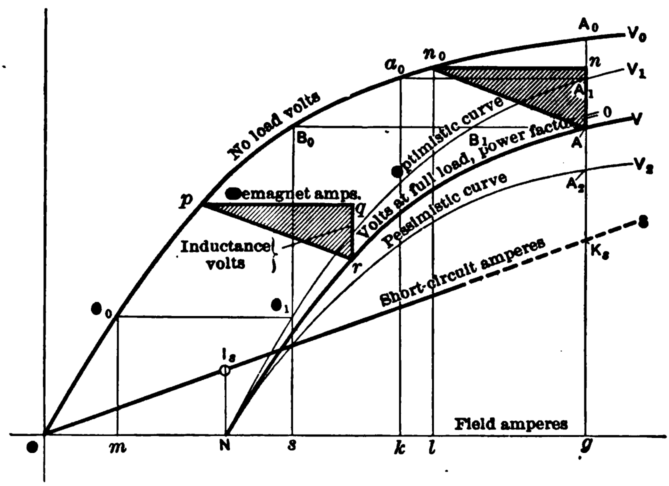


FIG. 430. Curves of voltage regulation of an alternator at zero power factor.

independent of its actual value, and depends on the field current and the armature current only.

Report. Plot the observed curves to field amperes as abscissæ (Fig. 430); determine per cent regulation at power factor zero. Figure out per cent regulation at power factor 100 per cent and 80 per cent by the method described in § 582, or by the more accurate method shown in § 583.

575. Regulation by Split-Field Test. — Instead of using a synchronous motor, one-half of the alternator under test may be converted into motor (Fig. 429): this is the same (Behrend's) method as is described in § 563 for determining efficiency, and in § 569 in application to temperature run. By suitably adjusting the field current on the "generator" and the "motor" side of the machine, a full-load current may be made to circulate through the armature. This current is practically

wattless, because of the high inductance and comparatively low resistance of the armature windings; thus the conditions are practically the same as with the machine loaded at a power factor zero.

The terminal voltage is determined either by a voltmeter, as explained in § 563, or is calculated from the so-called short-circuit curve (Figs. 430 and 431). The short-circuit curve is obtained by short-circuiting the armature windings upon themselves, through suitable ammeters, and gradually increasing the excitation, with the fields connected as in actual operation. The curve gives the values of the

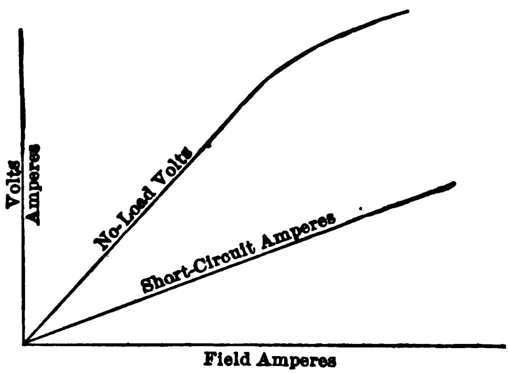


FIG. 431. No-load and short-circuit characteristics of an alternator.

field current necessary for driving different currents through the armature windings. It is usually a straight line, the saturation under the conditions of the test being quite low.

The short-circuit curve is used for calculating the fictitious terminal voltage of a machine with fields connected as in operation, in the following way: Assume for a moment that the "generator" half and the "motor" half are two separate machines. The voltage gA at the generator terminals is equal to the sum of the motor counter-e.m.f. plus an excess voltage, necessary for driving the current through the impedance of the motor armature. It will be seen from Fig. 423 that when the power factor is zero, the two latter e.m.f.'s are simply added arithmetically, and not vectorially. Referring again to Fig. 430, let Og be the excitation of the generator, and Om that of the motor. Also let ON be the field-current necessary for driving the full-load current NI_s through the armature windings (here we make use of the short-circuit curve).

Thus, the generator must supply ampere-turns Om and ON to balance the action of the motor. Making $ms = ON$, we obtain the total excita-

tion Os necessary for balancing the action of the motor. To this excitation there corresponds the voltage sB_0, which the generator has to supply at its terminals. On the other hand, the actual excitation of the generator is Og; having the two points B_0 and g, we find the point A on the required regulation curve NV. Other points on the curve NV are constructed by using different pairs of values of Om and Og, obtained from the test.

The method is strictly correct only when the saturation curve between O and B_0 is practically a straight line, so that the exciting current is proportional to induced voltages; this is very nearly the case under the conditions met with in practice.

We assumed in the above, that the generator and the motor are two separate machines, and showed how to figure out the terminal voltage gA without actually measuring it. The method can be applied directly to a machine with two halves connected in opposition, as in Fig. 429 where the separating points between the "generator" and the "motor" side of the armature are not accessible, since they travel synchronously with the field. The reasoning is exactly the same as above; it is not necessary to divide by two the induced voltages or the short-circuit current, as it may seem at first on the ground that only one-half of the armature coils are active. A little consideration will show, that the numerical relations are exactly the same as if the whole machine were used as generator, or as motor.

576. EXPERIMENT 27-F. — Regulation of an Alternator from Behrend's Split-Field Test. — The purpose of the experiment is to determine the regulation of an alternator at power factor zero. The theory of the method is explained in the preceding article; the connections are shown in Fig. 429.

(*a*) Bring up the field current on both sides as high as possible, and reduce it on the " motor " side, until a full-load current flows through the armature. Read the voltage across one set of armature coils, as explained in § 563, and exciting amperes in both halves of the field. Gradually decrease the field current on both sides, so as to keep the armature current constant. Read again: field amperes, the voltage across the armature coil, etc. Take similar curves with other values of armature current.

(*b*) After this test take the no-load saturation and the short-circuit curves, as in Fig. 431, and measure the resistances of the armature windings.

Report. Plot the curves OV_0, OS, and NV, as in Fig. 430. See if the terminal voltages measured by the voltmeter check with those

predetermined from the short-circuit curve. Figure out per cent regulation at power factor zero, 80 per cent, and 100 per cent, as explained in §§ 582 and 583.

577. Optimistic and Pessimistic Limits of Regulation. — The question of predetermination of regulation of alternators, without an actual load test, must be considered as only partly solved at present. The methods in use are but approximations to the actual complicated phenomena of armature interference. At the same time, it is a comparatively easy matter to predetermine *the limits* NV_1 and NV_2 (Fig. 430) between which lies the true regulation curve NV. These limiting curves are strikingly called by Mr. Behrend the "optimistic" and "pessimistic" curves. They are useful in cases in which it is impossible to get the true regulation curve, or where it is deemed sufficient to know the limits.

The optimistic and the pessimistic curves may be easily plotted from the no-load saturation curve OV_0 and the short-circuit curve OS. It is explained in § 320 that the armature interference (neglecting ohmic drop) is caused partly by armature reaction, partly by armature inductance. The optimistic curve is obtained on the assumption that *all* of the armature interference is caused by the armature reaction, the pessimistic curve — on the assumption that *all* of it is caused by the inductance.

(*a*) The reasoning in plotting *the optimistic curve* is as follows: When the armature is short-circuited, and a rated current NI_s flows through it, the armature ampere-turns are equal to the field ampere-turns, because no field is left to induce a voltage for the external circuit. Therefore ON represents the demagnetizing armature ampere-turns with full-load current. These ampere-turns are the same at any terminal voltage, provided the current is the same and the power factor is near zero, as on short-circuit test. Thus, if an excitation Os is necessary to produce a certain voltage sB_0 *at no load*, an excitation larger than this by the amount equal to ON is necessary to produce the same voltage *with full-load wattless current* flowing through the armature. Plotting $B_0B_1 = ON$ we obtain a point B_1 on the full-load regulation curve NV_1.

The reasoning is the same for all points on the curve NV_1; they are obtained by merely plotting segments C_0C_1, B_0B_1, a_0A_1, etc., equal to ON. This would be correct, if the no-load saturation curve OV_0 were a straight line, so that the same number of ampere-turns ON would equally affect the voltage with all values of the exciting current. As this is not the case, the curve NV_1 is not the true regulation curve. A little consideration will show, that it gives values of terminal

voltage which are too high; for this reason it is called the optimistic curve.

(*b*) In plotting *the pessimistic curve* it is assumed that all the drop in the armature is caused by the inductance of the armature windings, as in Fig. 251. Take a point K_s on the short-circuit curve, such that the current gK_s equals 3 times the normal current NI_s. It takes the voltage gA_0 to drive this current through the armature; hence, to drive the current NI_s through the armature, with the same excitation Og, would take only one-third of the same voltage. Let A_0A_2 be $= \frac{1}{3}\, gA_0$; then the rest of the voltage, gA_2, is available in the external circuit. Repeating a similar operation for other points on the curve OS, and connecting the points, such as A_2, the pessimistic curve NV_2 is obtained.

A simple method for locating points on the pessimistic curve is as follows: To find the point corresponding to an ordinate, such as gA_0, connect O to A_0 and from N draw a parallel to OA_0; the point of intersection A_2 of this parallel with gA_0 lies on the pessimistic curve. To prove this, denote gA_0 by y and gA_2 by y_2, and suppose the current gK to be n times larger than the rated current NI_s. It takes a voltage y to drive the current gK_s through the armature; consequently, it will take $y \div n$ to drive NI_s through the armature. The rest, y_2, is available at the terminals of the machine. We have, thus:

$$y_2 = y - (y \div n),$$

or

$$\frac{y_2}{y} = \frac{n-1}{n} = \frac{gK_s - NI_s}{gK_s}.$$

But

$$\frac{gK_s}{NI_s} = \frac{Og}{ON};$$

substituting, we find

$$\frac{y_2}{y} = \frac{Og - ON}{Og} = \frac{Ng}{Og}.$$

Consequently, the line connecting the points O and A_0 is parallel to that connecting N and A_2; whence the above construction.

The reasoning in constructing the pessimistic curve would be correct if it were not for the effect of saturation in iron; a little consideration will show that the points, obtained by the method described above, lie below the actual regulation curve, whence the name pessimistic curve.

It is interesting to note, that if the no-load saturation curve OV_0 were a straight line, both the pessimistic and the optimistic curves

would coincide, and would be represented also by a straight line parallel to the no-load saturation curve and passing through the point N.

578. EXPERIMENT 27-G. — Determination of Limits of Regulation of an Alternator. — The purpose of the experiment is to obtain the optimistic and the pessimistic curves of an alternator, as explained above (Fig. 430). The necessary tests comprise the determination of the no-load saturation curve and the short-circuit curve, Fig. 431. It is generally known that polyphase machines give better regulation than single-phase machines. To observe this, take one short-circuit curve with but one phase short-circuited, and another with three phases short-circuited. When a phase is short-circuited between the terminals, with the machine Y-connected, two phases of the winding are connected in series. It is interesting to take a third short-circuit curve, with one phase short-circuited between the terminal and the neutral point. In performing this test, measure the open-circuit voltages in the two other phases.

Report. Plot, for the three-phase machine, all the curves shown in Fig. 430, except the actual regulation NV, unless it has been determined from a previous test, for instance as in § 574. Plot similar curves for the machine running single-phase, and compare the results corresponding to the same value of field current. Plot also the voltages induced in the phases which were not short-circuited, and explain the physical meaning of these voltages. If actual regulation tests on the machine are available, show that with the three-phase machine the actual regulation is nearer to the optimistic limit than with the single-phase machine. In comparing the single-phase and the three-phase data do not forget to reduce the voltages to the same number of turns per phase.

579. Predetermination of Regulation by Torda-Heymann Method. — The optimistic and the pessimistic curves (§ 577), which give two limits of actual voltage regulation, would coincide if the no-load characteristic were a straight line (Fig. 430). In good modern two-phase and three-phase machines the actual regulation is considerably closer to the optimistic than to the pessimistic limit, the influence of the armature reaction being much more prominent than that of the inductance of the armature winding.

On the basis of these two facts, Dr. Torda-Heymann* developed a method of predetermination of regulation, in which the "optimistic" method of construction is used, but the curve obtained is corrected for the effect of saturation in iron, and thus is made to represent the

* *Electrician* (London), 1904, Vol. 53, p. 6.

actual regulation of the machine. The effect of saturation Dr. Torda-Heymann expresses in what he calls the "apparent reluctance" of the machine, or the ratio of the exciting ampere-turns to the corresponding magnetic flux at no load. But the exciting ampere-turns are proportional to the field current, and the flux is proportional to the induced voltage. Hence, referring to Fig. 432, the apparent reluctance at the field current Og is proportional to the ratio $Og \div gA_0$. The coefficient

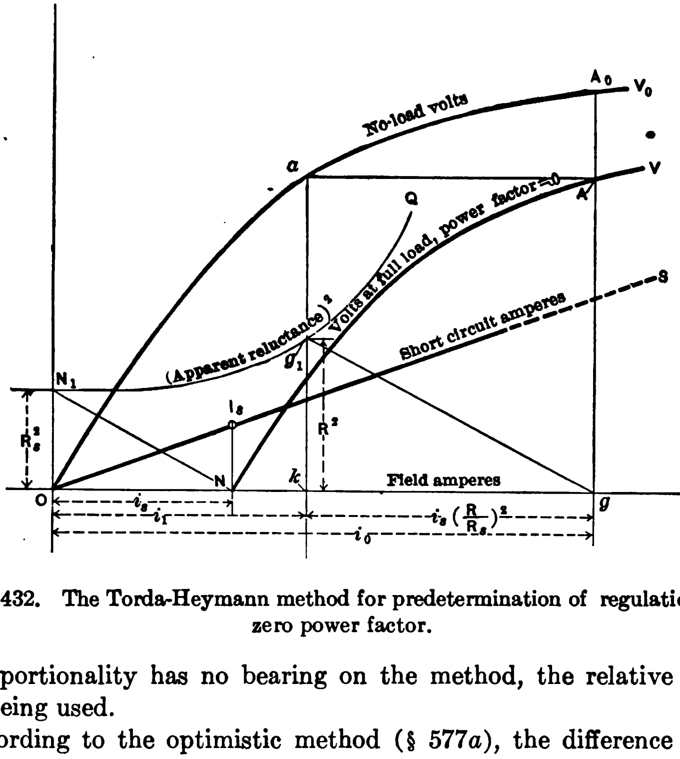


FIG. 432. The Torda-Heymann method for predetermination of regulation at zero power factor.

of proportionality has no bearing on the method, the relative values only being used.

According to the optimistic method (§ 577a), the difference kg between the abscissæ at no load and at full load corresponding to the same terminal voltage is equal to ON (Fig. 430), or with the notations in Fig. 432, $i_1 = i_0 - i_s$. This is incorrect, on account of the effect of the armature inductance. In reality, kg, or aA, is larger than ON; in other words $i_1 < i_0 - i_s$. Dr. Torda-Heymann corrects the preceding equation in a semi-empirical way, by multiplying the short-circuit current by a coefficient larger than unity. He assumes this coefficient to be a function of saturation in the machine, and puts

$$i_1 = i_0 - i_s \cdot f(R),$$

where R is the *apparent reluctance* of the machine, as defined above.

Dr. Torda-Heymann has found theoretically and confirmed by the results of various tests that the function $f(R)$ may be represented, with a sufficient accuracy, by the ratio $(R \div R_s)^2$, where R is the reluctance corresponding to the actual saturation at the point k (Fig. 432), and R_s is the lowest limit of reluctance with no saturation whatever. Thus he gets

$$i_1 = i_0 - i_s \cdot \left(\frac{R}{R_s}\right)^2.$$

In order to construct the curve NV of actual regulation at power factor zero, from the no-load and short-circuit curves, according to Torda-Heymann's method, plot first the curve $N_1 Q$ giving, to any arbitrary scale, apparent reluctances *squared*, preferably to such a scale that $ON_1 = 1$, 10, 100, etc. Take an exciting current, such as Ok, calculate the value $kg = i_s \ (R \div R_s)^2$ and thus locate the point g. Complete the rectangle $gkaA$; the point A lies on the required voltage regulation curve. The point g may also be located graphically by drawing g_1g parallel to N_1N; this may be easily proved from the similarity of the triangles g_1kg and N_1ON.

Torda-Heymann's method should be considered as a semi-empirical one, because of the correction $(R \div R_s)^2$; but it gives good results in practice. It is also quite flexible, because the correction may be given any other form to suit a particular type of alternator.

580. EXPERIMENT 27-H. — Predetermination of Regulation of an Alternator by the Torda-Heymann Method. — The curves required are the no-load saturation and the short-circuit curve (Fig. 431). The experiment is performed exactly as in § 578. In fact, the same data may be used for working out the results of both experiments. It is well to have an actual regulation curve, determined experimentally, so as to check it with the predetermined regulation, according to the Torda-Heymann method.

581. Regulation at Power Factors other than Zero. — With non-inductive load the current in the armature reaches its maximum in the relative positions of the poles and the conductors shown in Fig. 249. The reaction of the armature consists in this case in a strengthening of the original field on one side and a weakening of it on the other side of each pole. By following the armature interference from point to point in various positions of the armature winding, it may be shown that the armature reaction only distorts the field instead of weakening it, as when the power factor is zero (Fig. 250). Such a reaction is sometimes called the transversal reaction, while the demagnetizing action is known as the direct reaction. With power factors between zero and

100 per cent both kinds of armature reaction are present simultaneously. This circumstance makes the theoretical evaluation of the armature reaction, and the predetermination of voltage drop, rather intricate; the problem cannot be considered at present as solved, at least for practical uses. The methods described below are but a rough approximation to the actual conditions, but are used for the lack of a more accurate method.

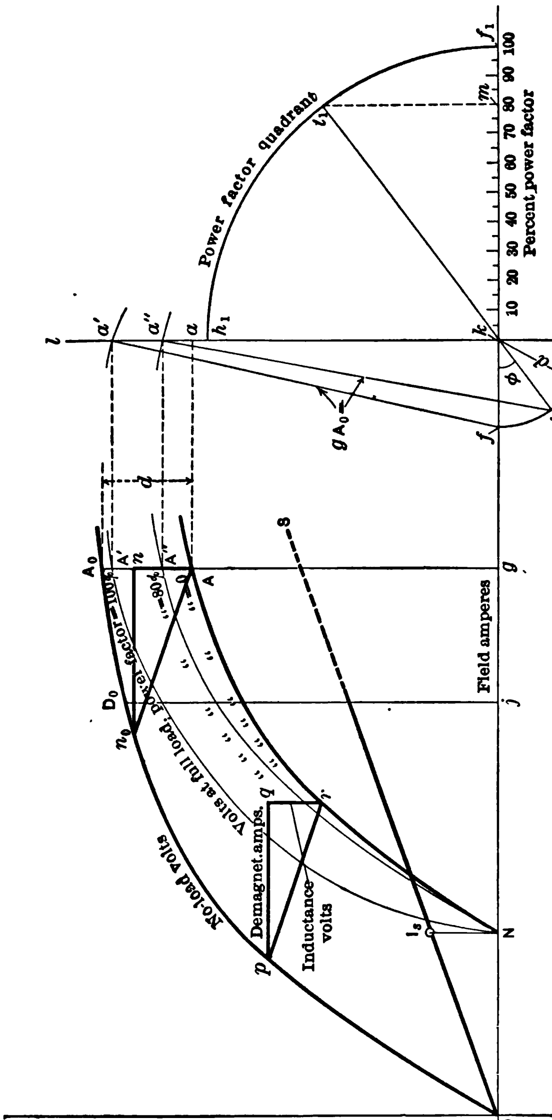


FIG. 433. Predetermination of voltage regulation of an alternator, at power factors other than zero.

582. Kapp's Diagram. — Kapp's method for predetermining regulation of alternators, at power factors other than zero, is shown in Fig. 433. The curves OA_0 and NA are the same as in Fig. 430, and are supposed to be determined from experimental data. Referring to the vector diagram, Fig. 252, the inductive drop ix is in phase with the terminal voltage E, when the power factor of the load is zero. Moreover, neglecting the ohmic drop ir, the

induced e.m.f. E_0, and the terminal voltage E, are in this case in phase with each other, and the inductive drop is an *algebraical* difference of the two. At other values of power factor it is a *geometrical* difference of the two. In Fig. 433, gA_0 is the induced voltage, gA is the terminal voltage, and AA_0 is the total drop at power factor zero, due to both armature inductance and armature reaction.

At any other value of power factor, these three vectors form a triangle, such as kta'', the angles depending upon the power factor of the load. The side $ta'' = gA_0$ represents the no-load voltage; the side $tk = AA_0$ is the drop in the armature. Their difference ka'' represents the terminal voltage of the machine at this particular power factor, and at the same current, to which the curve NA refers. Projecting a'' on the ordinate gA_0, the point A'' is obtained on the regulation curve for this power factor. At a power factor of 100 per cent, the triangle assumes the aspect fka'; at a power factor zero it is reduced to a straight line hka, similar to gAA_0. If complete regulation curves are desired, the same construction must be repeated for other ordinates of the saturation curves OA_0 and NA.

In order to read the power factor directly, it is convenient to draw the power factor quadrant $h_1t_1f_1$ with a radius such that it may be conveniently divided into 100 parts. The power factor is then read in per cent on the radius kf. This is evident when we remember that km is proportional to the cosine of the angle ϕ, and this cosine, by definition, is the power factor of the load.

An objection to this method of predetermining regulation of alternators is that it combines into one vector $A_0 A$ all the factors of the armature interference, which factors in reality follow different laws. A more accurate method is that by Potier described in the following article.

583. Potier's Diagram. — The method is similar to that shown in Fig. 433, except that the armature reaction is separated from the armature inductance before the diagram is constructed. Referring to Fig. 430, let n_0n represent the demagnetizing ampere-turns on the armature; when the exciting current is $= Og$, the actual excitation corresponds to Ol, the rest, lg, being destroyed by the armature reaction. To the excitation Ol corresponds the induced voltage ln_0, or ng. From this voltage the inductive drop nA must be subtracted, giving the terminal voltage gA. Thus, the total action of the armature interference is represented by the triangle n_0nA, n_0n representing the action of the armature reaction, nA that of the armature inductance. This triangle shows also the errors inherent to the pessimistic and the optimistic methods (§ 577). In the optimistic method, the horizontal line

a_0A_1 is taken instead of the hypothenuse n_0A; in the pessimistic method A_0A_2 is taken instead of the same hypothenuse n_0A.

If n_0A were known in its magnitude and direction, the regulation curve NV could be easily plotted from the no-load curve OV_0 by drawing parallel lines, such as n_0A, pr, etc. On the other hand, when OV_0 and NV are given, the vector n_0A may be determined by trials. Potier makes a tracing of the curve NV and moves this parallel to itself until it coincides as closely as possible with the curve OV_0. The direction of the movement determines the position and the magnitude of n_0A. Having found n_0A, the demagnetizing ampere-turns n_0n and the inductive drop nA are easily found.

Now Potier assumes, that the demagnetizing ampere-turns n_0n are the same with all values of power factor, but are subtracted geometrically, instead of arithmetically, from the field excitation Og. This gives again a diagram similar to that shown on the right side of Fig. 433, except that exciting amperes are used instead of corresponding voltages. The radius $kt = n_0n$; $ta'' = Og$. The result, ka'', gives the effective ampere-turns at the power factor corresponding to the angle ϕ. Plotting $Oj = ka''$, we find the voltage jD_0 actually induced in the armature. From this voltage, the inductive drop nA must be subtracted geometrically, as in Fig. 252, in order to obtain the terminal voltage at this load. If greater accuracy is required, the ohmic drop ir shown there may also be taken into account.

The angle ϕ, used in the construction of the triangle tka'', is not quite correct, since it must be the phase displacement between the *induced* voltage and the current, and not that between the *terminal* voltage and the current. Having constructed the diagram shown in Fig. 252, the angle AOD may be used for constructing the triangle tka'' in a second approximation, new value of ka'' found, etc.

The Potier method is not quite correct, because the armature reaction varies in reality, according to a much more complex law than is assumed there.

584. Literature References. — Those especially interested in the difficult question of regulation of alternators will find further information in the following publications:

Guilbert, A series of articles on the subject in the *Electrical World*, 1902–1903.

Torda-Heymann, *Electrician* (London), 1904, Vol. 53, p. 6.

Hobart and Punga, *Trans. of the A.I.E.E*, 1904, p. 291.

Blondel, *Trans. Internat'l Elec. Cong.*, 1904, Vol. 1, pp. 620 and 635.

Rushmore, ibid., p. 744.

Henderson and Nicholson, *Journal of the Inst. of Elec. Engs.* (British), 1905, p. 465.

Rushmore's article has quite a complete bibliography on regulation of alternators up to 1904. A compromise between an experimental determination and a predetermination of the regulation curve at power factor zero is made possible by the methods of Blondel and Fischer-Hinnen, in which but one point of the curve NA needs to be determined experimentally (Hay, *Alternating Currents*, p. 160).

A clear elementary treatment of the question of regulation of alternators will be found in Thomälen's *Text-book of Electrical Engineering*, Chap. XIII. For a more advanced and thorough exposition the reader is referred to Arnold and La Cour, *Die Synchronen Wechselstrommaschinen*, Chapters II and III. The armature reaction is treated there, in accordance with Blondel's investigations, as consisting of two components, the demagnetizing ampere-turns and the cross-magnetizing (or distorting) ampere-turns. The influence of each component is determined separately.

Blondel's theory of two armature reactions forms the basis of a series of "*Essays on Synchronous Machinery*" by V. Karapetoff, in the *General Electric Review*, 1911.

CHAPTER XXVIII.

THE ROTARY CONVERTER.

585. In certain cases of engineering practice it is necessary to transform direct current into alternating current, or vice versa. The most important case of this kind is in connection with electric railways, where high-tension alternating currents delivered from the power house are converted into 500 volts direct current in so-called substations which supply the trolley lines with current.

One of the possible solutions for converting alternating into direct current is to use a motor-generator set. An induction or synchronous motor is direct-connected to and drives a direct-current generator; the

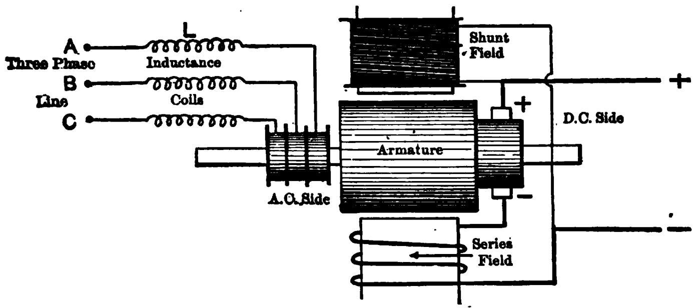


Fig. 434. A compound-wound three-phase rotary converter.

energy supplied to the motor in the form of two- or three-phase current is in this way transformed into direct current.

Another solution is to use the so-called *rotary converter,* which is a combination *in one machine* of a synchronous alternating-current motor and a direct-current generator.

586. General Description of the Rotary Converter. — A rotary converter is shown schematically in Fig. 434. In its construction it resembles a direct-current machine (Fig. 192), only, in addition to a commutator and brushes for direct current, it has two or more slip rings, connected to the same armature winding as the commutator. Fig. 435 shows diagrammatically the armature winding, the commutator, and the slip rings of a two-pole, single-phase rotary converter.

Fig. 436 shows a similar machine, provided with three slip-rings for converting three-phase currents into direct currents, or vice versa.

The action of a rotary converter can be understood from these two figures. When a machine such as is there shown, is driven mechanically, as a generator, it delivers direct current through the commutator and the brushes K, L, at the same time delivering an alternating current through the collector rings A, B, or A, B, C. When so doing, it is called a *double-current* machine. The direct and the alternating currents are superimposed in the armature, but are used in separate external circuits. Now, both direct- and alternating-current generators are invertible in their action. A direct-current generator may be converted into a direct-current motor, and an alternator into a synchronous motor. So, when direct current is sent from outside through the terminals L and K of the machine, it runs as a direct-current *motor:* at the same time it can continue to supply alternating current from its collector rings. In this case it acts as a rotary converter, *receiving* direct current and *delivering* alternating current. The more power is taken from the alternating-current side, the larger becomes the direct-current input; the latter being always equal to the output plus the losses in the machine itself. Instead of driving the rotary as a direct-current motor, it can be driven from the alter-

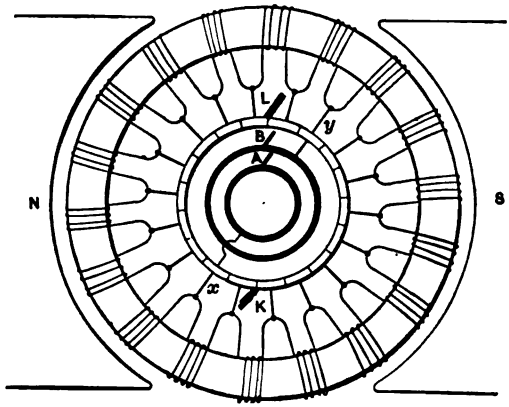


FIG. 435. Armature connections in a single-phase rotary converter.

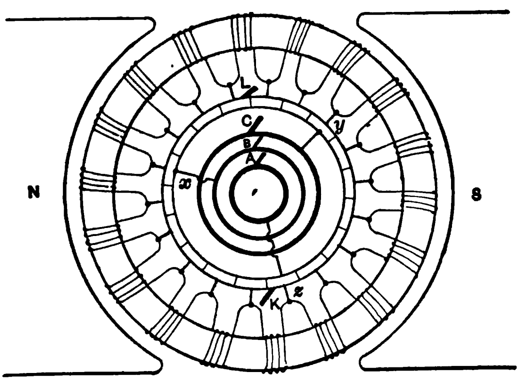


FIG. 436. Armature connections in a three-phase rotary converter.

nating-current side, as a synchronous motor; then direct-current power is available, as an output, at the commutator side of the machine. This is the way in which rotary converters are used in railway work. The above-described rotary converters are two-pole, ring-wound machines. Commercial rotaries are multipolar, polyphase, drum-wound machines, and represent a development of the above simplest type.

Rotary converters are provided with two, three, four or six slip-rings, according to the number of phases of the alternating-current supply. Single-phase converters are seldom used; three-phase machines are provided with three slip-rings, two-phase rotaries have four slip-rings. Very large rotary converters are sometimes supplied with six slip-rings, and the three-phase supply is converted into a six-phase system by means of special transformers (see § 542).

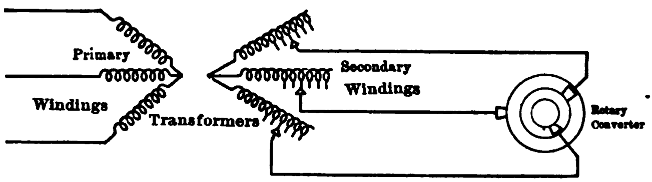


FIG. 437. Starting a rotary converter at a reduced voltage.

It can be proved theoretically that, with the same output, the I^2R loss in the armature decreases with an increasing number of slip rings; the reason being that the alternating-currents are more uniformly distributed in the armature winding. Thus, a six-phase rotary converter has a higher efficiency than a four slip-ring (two-phase) rotary converter; the three-phase rotary converter has a slightly lower efficiency than the two-phase rotary converter. All polyphase rotaries are considerably superior to the single-phase rotary, in that they give a larger output with the same size machine, and can stand a higher overload without falling out of step. This is due to the revolving field produced in the armature by polyphase currents.

587. Starting Rotary Converters. — Rotary converters, used for converting direct current into alternating, are started as ordinary shunt motors, and are brought up to the speed corresponding to the desired frequency of alternating current. If the rotary is intended to be run from the alternating-current side, as is the case in railway substations, it must first be brought up to the required speed and *synchronized* (§ 327), as any alternator or synchronous motor. Three methods are used for starting and synchronizing rotary converters:

(1) The rotary is started from the direct-current side, as a shunt motor, and synchronized by regulating the field and the starting resistance.

(2) A small induction (or direct-current) motor is provided on the shaft of the rotary converter; this motor being used for bringing the machine to the required speed.

(3) The rotary itself is converted into an induction motor during the period of starting, by opening its field circuit and switching the alternating current on the armature. A revolving field is thereby produced in the armature; this field induces eddy currents in the pole-pieces, which act as the squirrel-cage secondary of the induction motor. The machine starts, and when synchronism is reached, the direct-current excitation is switched on; the rotary continues to run as a synchronous motor. It is not advisable to start rotaries in this way on full voltage because of the inrush of current which may damage the machine itself, or be objectionable for the line. Taps are usually provided on the transformers for starting rotaries at about one half of the rated voltage (Fig. 437).

588. EXPERIMENT 28-A. — Exercises in Starting Rotary Converters. — The purpose of the exercise is to make clear the three methods of starting explained in the preceding article. Wire up the machine on the direct-current side as a shunt-wound motor (Fig. 212); on the alternating-current side provide synchronizing lamps, or a synchroscope (§§ 328 and 329).

(1) Start the machine from the direct-current side and bring it up to the right speed by regulating the field current and the starting rheostat, if necessary. Synchronize the machine as is done in the case of alternators. When the machine is in synchronism, close the main switch on the alternating-current side, and open the main switch on the direct-current side, taking care not to open the field circuit of the machine. The rotary will continue to run as a synchronous motor, supplying its own excitation, and may be loaded electrically on the direct-current side.

(2) Now provide a small induction motor, either belted or direct-connected to the rotary, and start the rotary by means of this motor. When synchronism is reached, switch the rotary on to the alternating-current line and open the auxiliary-motor circuit. In using this method of starting, it is convenient to have the secondary resistance of the induction motor adjusted so that the motor brings the rotary exactly to the required speed. If this is not feasible, some resistance is connected between the slip rings of the rotary converter. This resistance

constitutes a load which can be adjusted so that the induction motor will bring the rotary exactly to the required speed, and thus save time in synchronizing.

(3) After having practiced sufficiently with the above two methods of starting, the student may try to start the rotary converter from the alternating-current side by utilizing the eddy currents induced in the pole-pieces and dampers (Fig. 442). In performing this experiment, it must be borne in mind that the rotary, in starting, takes several times its normal current, so that the line should be suitably protected by fuses, or circuit-breakers. Another important precaution is to protect the field winding against high voltages induced in it by the revolving flux produced by the armature. This is done by subdividing the field winding into sections by suitable switches. *Never touch the field circuit* when the machine is being started from the alternating-current side, as the induced voltages may be dangerous to life. They gradually decrease to zero, as the machine approaches synchronism. Then the direct-current excitation is switched in, and the machine continues to run as a synchronous motor. Try starting at various voltages (Fig. 437), and measure current inrush and time which it takes to bring the rotary up to synchronous speed; also measure voltages induced in the field winding.

Report. Give diagrams of the exact connections used in the three methods of starting; give starting currents and voltages; time which it took in each case to bring the rotary to synchronism, and total time required to have the rotary running in regular operation. Give your opinion as to which method of starting is preferable in certain cases.

589. Ratio of Voltages on Direct- and Alternating-Current Sides.—There is a definite ratio between the direct- and the alternating-current voltages in a rotary converter, since both are induced in the same winding. In the single-phase rotary converter (Fig. 435) the maximum instantaneous value of alternating voltage is equal to the direct voltage: This is because the induced e.m.f. is the same between the direct-current brushes and the alternating-current brushes, when the points x and y of the winding come under the brushes K and L. At the same time this is the largest alternating voltage that can be induced in the armature. Therefore, the effective value of the alternating voltage is

$$1 \div \sqrt{2} = 0.707$$

times direct-current voltage. For instance, if it is desired to have 550 volts on the direct-current side, $550 \times 0.707 = 388$ volts must be applied between the collector rings A and B.

The same ratio 0.707 holds true for the two-phase rotary converter, provided the voltage is measured between the slip-rings a and b, or c and d, belonging to the same phase (Fig. 438). Otherwise the ratio is again reduced in proportion to $1 \div \sqrt{2}$ (Figs. 403 and 404), so that the effective voltage, for instance between a and c, or a and d, is only one-half of the direct-current voltage.

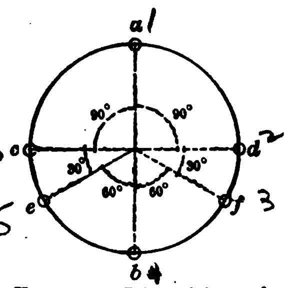


FIG. 438. Disposition of taps to six slip-rings, for producing either single-phase, two-phase, or three-phase currents.

If taps for the slip-rings are taken at a distance less than 180 degrees, such as, for instance, a and e in Fig. 438, the alternating-current voltage between these slip-rings is reduced in the ratio AC to AB (Fig. 439), where AB represents the voltage induced between two slip-rings connected to the armature at points 180 electrical degrees apart. It may at first seem that the voltage between the points A and C is to the voltage between the points A and B as the lengths of the corresponding arcs. However, a glance at Fig. 435 will show that the voltages induced in separate coils of the armature reach their maximum at different times, and must therefore be added geometrically. The sum of the infinitesimal arcs between A and C is the chord AC, and the same is true for the chord AB.

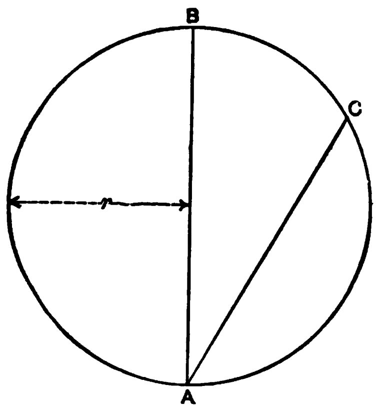


FIG. 439. Ratio of voltages in a rotary converter.

In a three-phase rotary (Fig. 436) the chord AC corresponds to 120 degrees, so that

$$AC = \tfrac{1}{2} AB \cdot \sqrt{3} = 0.866\, AB.$$

This means that, assuming a certain voltage on the direct-current side, the voltage between the slip-rings of a three-phase rotary converter is only 86.6 per cent of that of a single-phase or two-phase rotary converter. It has been shown that the alternating voltage of a single-phase rotary converter is equal to 0.707 of the direct-current voltage. Therefore, the ratio between the A.C. and the D.C. voltages in a three-phase rotary converter is

$$0.866 \times .707 = 0.612.$$

It is desired that the student deduce, in a similar manner, the ratios

between the direct-current voltage and the alternating-current voltages in four-, six-, and twelve-phase rotary converters. These voltages correspond in Fig. 438 to the chords *b-c*, *b-e* and *e-c*.

590. EXPERIMENT 28-B. — Ratio of Voltages in a Rotary Converter. — A rotary converter convenient for such an experiment should have six slip-rings (Fig. 438), tapped at the points of the armature marked *a, b, c, d, e, f*. The taps are spaced so that voltages can be obtained corresponding to either 1, 2, 3, 4, 6, or 12 phases. Run the rotary from the direct-current side and measure all the possible combinations of voltages between the different slip-rings. Make several runs with different speeds, different values of field current and with various voltages at the direct-current brushes. For very accurate work the machine must be driven mechanically by some outside source of power in order to have two voltages from open circuit. For all practical purposes the converter may be run from either the direct or alternating-current side, without materially affecting the ratios of the voltages.

Report. Give the ratios of voltages, as calculated from the experiment, and compare them to the theoretical ratios derived above. Show whether these ratios vary with the voltage, speed and excitation of the machine, and give possible causes for this.

591. Ratios of Direct and Alternating Currents. — The ratio between the current taken in on the direct-current side of a rotary converter and that delivered on the alternating-current side may be easily deduced from the fact, that the power output is equal to the power input, less the losses in the armature itself. This, of course, refers only to the power component of the alternating current; the wattless component may have any value according to the properties of the load or the excitation of the machine (§ 551). Suppose, as an example, that a three-phase rotary connected to a 110 volt direct-current supply, is delivering 12 kilowatts of non-inductive power on the alternating-current side. The currents on both sides of the rotary can be figured out as follows: The three-phase voltage (disregarding voltage drop) is equal to a 110 × 0.612 = 67.3 volts. To deliver 12 kilowatts at this voltage a current of

$$\frac{12000}{67.3\sqrt{3}} = 103 \text{ amperes per phase}$$

is required. If there were no losses in the armature, the direct current input would also be 12 kilowatts, or

$$\frac{12000}{110} = 109 \text{ amperes.}$$

To this current must be added a small current necessary for supplying the armature losses. This latter current is determined by running the machine at no load; it is used for overcoming iron loss and friction of the machine.

If, in the above example, the load were inductive, the power supplied from the direct-current side would still be the same, as long as the *true* power remains equal to 12 kilowatts. The necessary wattless component of the current is generated in the armature itself, without being supplied from the direct-current line.

When a rotary converter is running from the alternating-current side, supplying a load on the direct-current side, the *watts* input is equal, as before, to the watts output on the direct-current side, plus the losses in the machine itself, but the alternating *amperes* may vary within comparatively wide limits, with the same direct-current output. This is due to the rotary converter taking in a leading or lagging wattless component according to the value of field excitation. In this respect it is similar to the synchronous motor (§ 551). Knowing the output of the machine and the ratio of the voltages, the power component of the alternating current may be calculated; it represents the lowest limit of alternating current possible with a given direct-current load. The rotary converter may be made to actually take in this minimum current, at a certain value of field current. By strengthening the field, the converter is made to take in a leading component, in addition to the power component; by weakening the field a lagging component is taken from the line (Fig. 422).

592. EXPERIMENT 28-C. — Operating a Single-Phase Rotary Converter from the Direct-Current Side. — Start the rotary from the direct-current side, as a shunt-wound motor; provide inductive and non-inductive load for the alternating-current side, as in the case of a single-phase alternator (Fig. 248). Keep the voltage on the direct-current side and the field current constant, adjusting the latter so as to have the required speed at no load. This speed must be such as to give the rated frequency for which the rotary converter is designed. First apply a non-inductive load, read volts and amperes on both sides, and the speed of the machine. Take a series of such readings from no load up to about 50 per cent overload. Make similar runs at lower values of power factor, keeping it constant for each run. Or else, keep amperes constant during each run, and vary the power factor, as in Fig. 253.

The student must be careful not to let the machine run away while loading it on reactances. Wattless currents, flowing in the armature,

weaken the original field; this has the familiar effect of increasing the speed of the direct-current motor. Some rotaries are provided with a centrifugal speed-limiting device which opens the direct-current circuit, as soon as the speed exceeds a certain predetermined limit. It is well to repeat the same experiment with several values of field current and of the voltage at the direct-current terminals.

In the above test both the frequency and the alternating voltage are variable. In practice either one of them or both are required to be kept constant. This can be done within certain limits by regulating the field current and the direct-current voltage. Take a few readings of this kind, in order to determine the limits within which field current and direct-current voltage must be varied in order to keep either the alternating voltage, or the frequency, or both, constant.

Report. Plot to amperes input into the armature, direct and alternating voltages, amperes output, speed, and efficiency. If possible, plot on the same curve sheet the values of the power factor, in order to show its influence on the speed of the machine.

593. EXPERIMENT 28-D. — Operating Two-Phase or Three-Phase Rotary Converters from the Direct-Current Side. — The experiment is performed in exactly the same way as the preceding experiment, except that the load is two-phase or three-phase, instead of single-phase. If performed on the same machine (Fig. 438), it will show to what extent the rotary is more efficient when the load is taken from three or four slip-rings than when it is loaded single-phase.

594. EXPERIMENT 28-E. — Operating a Single-Phase Rotary Converter from the Alternating-Current Side. — Connect up and synchronize the rotary, as explained in § 588; provide a load on the direct-current side, and have an ammeter in the field circuit. Adjust the field current so as to have a power factor of 100 per cent, with full-load current on the direct-current side. Vary the load, if possible, from zero to 50 per cent overload, without adjusting the field rheostat, thus allowing the field current to follow the variations of the direct voltage. This corresponds to the practical case of a fluctuating load, when the attendant does not adjust the voltage. Read amperes, volts and watts; also note the field current.

Repeat the same run with such an initial value of the field current as to give about ninety per cent lagging power factor at full load. Make a third run with 90 per cent leading power factor, under the same conditions of load.

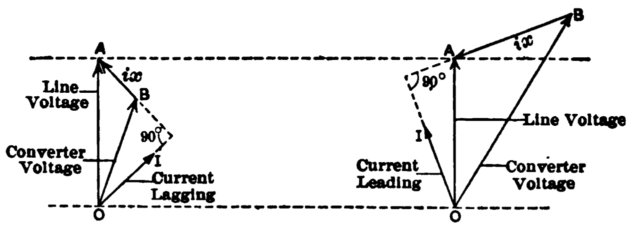
After this, make one or more runs with the field current constant. this is done by adjusting the field rheostat, before each reading. If

feasible, test the overload capacity of the rotary, by raising the load until the machine falls out of step. Be sure that the machine is not damaged by the overload, and that it is protected by a suitable circuit-breaker on the alternating-current side. Requirements for the report are similar to those in § 592.

595. EXPERIMENT 28-F. — Operating a Two-Phase or a Three-Phase Rotary Converter from the Alternating-Current Side. — The experiment is similar to the preceding one, and is intended to bring out the difference in the operation of a polyphase converter as compared to that of a single-phase machine. Note higher efficiency, better regulation, and larger overload capacity of the machine when operated two-phase or three-phase.

Report. See § 592.

596. Compounding Rotary Converters. — In many cases it is desirable to have rotary converters compounded, or provided with an additional series winding (Fig. 434), for the same reason that direct-



FIGS. 440 AND 441. Diagrams showing that presence of inductance raises voltage with a leading current, and lowers voltage with a lagging current.

current generators are compounded, viz., in order to have a constant voltage at variable load. It is sometimes advantageous to have the rotary even *over-compounded,* so as to compensate for voltage drop in long feeders (§ 228). It may at first seem that a series winding alone, shown in Fig. 434, should be sufficient to produce the desired effect. But, in an ordinary converter (without split poles), the ratio of alternating- to direct-current voltage is nearly constant, since they are induced in the same winding by the same magnetic field. Therefore, the only effect of a series winding would be to produce leading wattless currents which would weaken the field to nearly its original value. *In order to increase the voltage on the direct-current side, the alternating voltage must be raised accordingly.*

One way of accomplishing this result is to connect some inductance

in series with the alternating-current leads (Fig. 434) and to over-excite the machine by means of a series-field winding. An over-excited converter takes in leading currents, similarly to a synchronous motor (§§ 551–552). The effect of the inductance with leading and with lagging currents is shown in Figs. 440 and 441.

OA represents the constant line-voltage, and OB the voltage at the slip-rings. In the diagram to the left, the machine is under-excited, and therefore the current is lagging. The line voltage is the geometric sum of the converter voltage and the drop in the inductance. The latter leads the current in phase by 90°, and is represented by BA. It will be seen that OB is smaller than OA, so that the presence of the inductance makes the conditions more unfavorable for the converter. On the contrary, when the current is leading (diagram to the right) the triangle OAB is of such a shape that OB is larger than OA. This is because OA is given, and AB must be perpendicular to OI. Thus, *an inductance in series with the line helps to raise the voltage, provided that the rotary converter is compound-wound, or over-excited so that it takes in a leading current.* (See also § 598 below.)

597. EXPERIMENT 28-G. — Exercises in Compounding Rotary Converters. — Connect the rotary for running from the alternating-current side, and provide suitable inductance coils, as shown in Fig. 434. Apply a moderate load to the direct-current side, and vary the shunt-field current throughout wide limits so as to observe the combined action of leading currents and of the inductance in the line. The series field is not connected in during this test. Now, from the increase in the shunt current, necessary for keeping the voltage constant, figure out the required number of turns in the series winding, in order to produce the same effect automatically. If the number of turns of the shunt winding is not known, it can be determined as is explained at the end of § 229. Put the calculated number of series turns on the machine and verify the predetermined performance. Then increase the number of series turns so as to get a certain specified amount of over-compounding, and if the machine is over-compounded too much, put a shunt across the series winding, as is done in case of compound-wound generators (Figs. 199 and 200).

Change the inductance in the line, and repeat the same experiment in order to see the influence of the inductance on the number of series turns required for compounding. Take a complete curve of voltage regulation for at least one combination of inductance and series windings.

Report. Show by a diagram the connections used during the experiment; plot curves showing the variations of the current and watts input, power factor, and voltages with varying shunt-field current, with a constant direct-current load. Give the results of calculating the necessary number of series turns, and show in how far the actual performance checks with the calculations. Give results showing the influence of the change in inductance on the voltage characteristics of the machine.

598. Voltage Regulation of Rotary Converters. — The above-described method of maintaining a constant voltage on the direct-current side of a rotary converter, by a combination of inductance in the line and a series winding on the machine, has certain limitations. The following other methods are used in practice for voltage regulation:

(*a*) The secondary windings of the transformers supplying the rotary are provided with taps (Fig. 437) connected to a special switch or controller. By using different taps, the voltage between the slip-rings is varied within certain limits so as tc keep the direct voltage constant.

(*b*) Induction regulators, or transformers having a fixed secondary winding, and a primary winding which can be moved within certain limits so as to vary the inductive action between the two windings. The secondary winding is connected in series with the converter leads, the primary is connected across the line. Induction regulators can be operated either manually or by a small auxiliary motor. The action is often made automatic by connecting the motor through a voltage relay on the direct-current side.

(*c*) An alternating-current booster, direct connected to the converter and driven by it. The booster has a stationary field and a revolving armature. The winding on this armature is connected in series with the leads from the slip-rings to the converter armature. By varying the booster field the converter voltage is regulated.

(*d*) A direct-current booster, or a low-voltage direct-current machine in series with the direct-current line. The line voltage is regulated by varying the field excitation of the booster.

(*e*) Split-pole converter; see papers by Messrs. Stone, Woodbridge, and C. A. Adams, in the Trans. A. I. E. E., 1908.

599. Hunting and its Prevention. — A trouble called "hunting" is sometimes experienced in operating rotary converters. The pointers of the ammeters on the alternating-current side begin to swing without any corresponding changes in the load, and the machine begins to give

a humming noise, indicating that its speed varies periodically. This "pumping" grows worse and worse until the converter falls out of step, and the circuit-breakers on the alternating-current side open the circuit.

This trouble is supposed to be due to the natural period of swing of the rotary converter armature: anything unsteady in the circuit creates favorable conditions and intensifies these swings. Non-uniformity of rotation of the steam-engines, or a faulty governor may act as such factors, causing periodical inrushes of current into the armature of the rotary converter. If the impulses happen to occur at intervals sufficiently close to the period or to a multiple of the period of natural swing of the armature, the inrushes are intensified, causing still greater non-uniformity, etc.

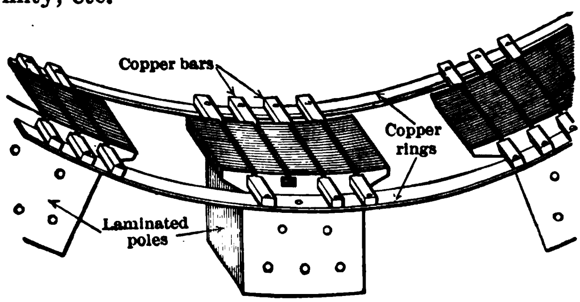


FIG. 442. Copper dampers on the poles of a rotary converter, to prevent hunting.

This phenomenon is much more noticeable with 60-cycle rotary converters, than with 25-cycle machines, because the former have more poles for the same speed; the angular distance between the consecutive poles is smaller, hence, the same angular deviation of the armature from its true position means a greater electrical deviation. For this reason some engineers object to using 60-cycle rotary converters, and prefer to use motor-generator sets, in which the synchronous motor and the direct-current generator may be given different numbers of poles. Sometimes induction motors are used in place of synchronous motors, and in this way all "hunting" troubles are eliminated.

The best remedy known against hunting is to provide the pole-pieces with so-called "dampers" (Figs. 424 and 442). The copper dampers, shown in Fig. 442, have the shape of a stationary squirrel-cage winding. Polyphase currents in the revolving armature produce a revolving flux which travels synchronously in the direction opposite to the rotation of the armature, and thus is stationary in space, merely strengthening or weakening the field produced by the poles. When, however, the armature is "pumping," the armature flux is no longer stationary in

space, but follows the oscillations of the armature. This swinging of the flux induces currents in the dampers: a heavy electromagnetic torque is produced, tending to keep the armature at the right speed. The action of the dampers is analogous to that of the squirrel-cage secondary of an induction motor.

Another remedy which may be used in the case of an emergency is connecting inductance coils in the alternating-current circuit, whether there is a series winding or not (Fig. 434). Such inductance coils limit the inrush of current during oscillations and prevent them from attaining dangerous proportions. This remedy should not ordinarily be applied, since it means a considerable voltage drop and a poor regulation.

Still another remedy is to provide the rotary with a heavy fly-wheel, the inertia of which reduces oscillations of the revolving part. This is also a makeshift, but may be useful in the case of an emergency, especially with small rotaries.

600. EXPERIMENT 28-H. — Comparative Study of Remedies against Hunting. — This experiment can be performed only when conditions can be created in the laboratory, such as to produce appreciable hunting; for instance, by supplying the rotary with current from an alternator driven by a steam-engine having a high degree of non-uniformity of rotation. Synchronize the rotary and try to run it from the alternating-current side, first without any auxiliary appliances mentioned above. Then gradually introduce more and more self-induction into the line and observe the improvement in operation of the rotary. See what happens when more inductance is put in than is necessary. Take readings at no load, at a partial load, and at full load. There are two ways of expressing the "degree" of hunting or pumping. One is by per cent variation of angular velocity of the armature; the other, by per cent current fluctuations as shown on the ammeters. The non-uniformity of rotation may be observed on a sensitive tachometer, such as a magneto-generator connected to a milli-voltmeter. A chronograph may also be used, in the same way as for determining the degree of non-uniformity of rotation of steam- and gas-engines.

Disconnect the inductance coils, and have a fly-wheel direct-connected or belted to the rotary. See if this remedy is as efficient as the inductance coils, and note the performance of the rotary with and without the fly-wheel.

Finally provide the rotary with suitable dampers and investigate their influence at various loads.

Report the observed performance of the rotary, and your conclusions in regard to hunting and its prevention.

CHAPTER XXIX.

THE INDUCTION MOTOR — SPECIAL STUDY.

I. PREDETERMINATION OF PERFORMANCE.

601. ACTUAL load tests on induction motors, as well as on any other type of electrical machinery, are avoided, whenever possible, since they involve a considerable expenditure of energy, and special appliances, if accurate results are required. In machines beyond a certain size the waste of power and the arrangements for load make load tests practically impossible. Methods have been developed, therefore, for *predetermining* the performance of a machine, under actual load conditions, from a few simple readings taken at no load. Such a method in application to polyphase induction motors is given in the following articles.

The first step towards predetermination of performance is indicated in §§ 343 and 344, where it is shown that the output of an induction motor may be calculated from the input and the losses. But, a load test is necessary even there, in order to obtain the values of power factor and speed, corresponding to a given current input. It will be shown that power factor and speed may also be predetermined from no-load readings, thus making a load test with all its complications unnecessary.

602. Circle Diagram. — Let OE in Fig. 443 represent the impressed voltage in one of the phases, and OI the current in the same phase at a certain load; the angle ϕ between the two corresponds to the power factor of the motor at this load. *Theory and experiment show that, when load varies, the current changes in such a way that the locus of its vector is represented by a semicircle I_0IK.*

The current at no load is represented by the vector OI_0; the current is small and the phase angle EOI_0 large, the power factor being low. The no-load current may be considered as consisting of a wattless component Om, which produces the magnetic flux, and of a power component mI_0, which overcomes iron loss and friction in the motor. As the load increases, the point I_0 moves along the circle, the value of the current increasing, as well as the power factor. When the motor becomes overloaded the power factor decreases again, due to a more pronounced influence of the magnetic leakage. When the load is such

that the motor stops, the current which it takes at standstill is represented by a certain vector OI_s. The current OI_s is called the short-circuit current, or, more correctly, the current with the armature locked.

Thus, if the circle has been determined for a given motor, the power factor Cos ϕ may be measured from the diagram for any given value of the input current OI.

The proof of the proposition that the locus of the points, such as I, is a semicircle, is given separately in §§ 613 and 614. We will here

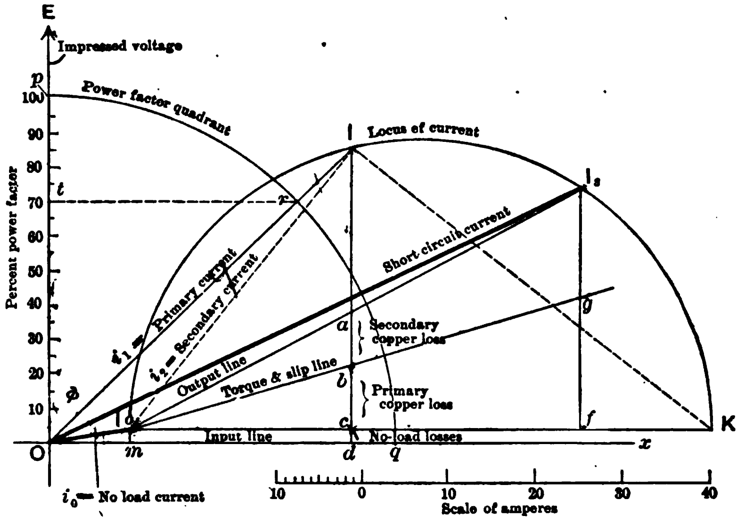


FIG. 443. The circle diagram for determining the performance of an induction motor (Heyland).

confine ourselves to the exposition of the application of the circle diagram. Apart from any theoretical proof, this may be accepted as a result of numerous direct experiments. It may be verified from any accurate load test by plotting the vectors of current to the observed values of the phase angle ϕ; it will be found that the load points lie on a semicircle.

The circle may be constructed by knowing only one point on it, if, in addition, the position of the point I_0 is known. As such a second point, the point I_s is usually selected, the vector OI_s representing the current with the armature locked. The vector OI_0 is known from the no-load readings. Thus, the construction of the circle is made possible from no-load readings, and readings with the armature locked. In both cases no brake is required, and the necessary measurements are both simple and accurate.

OI being the primary current, its component *Id* in phase with the voltage *OE* represents the working component of the current: hence, *Id* multiplied by the voltage gives true watts input per phase. Thus, the circle gives watts input and the value of the power factor, for any given value of the primary current.

Power factor Cos ϕ, equal to the ratio of *Id* to *OI*, can also be read directly in per cent on the quadrant *prq*. Namely, Cos ϕ is equal to the ratio of *Ot* to *Or*; but *Or*, the radius of the circle, being constant, Cos ϕ is directly proportional to *Ot*. By selecting *Op* equal to *Or* such as to be conveniently divided into 100 parts, power factor is read off directly in per cent, on the line *OE*.

It will now be shown, that output, torque, slip, efficiency — in fact all the data for plotting the performance curves (Fig. 271) — may be predetermined from the same circle diagram.

603. Graphical Representation of the Losses.—The current *cd*, equal to I_0m, represents the no-load losses in the motor, being the working component of the no-load current OI_0. Thus, *cd* accounts for the iron loss, friction, and for the copper loss corresponding to the no-load current.

We shall now prove that *ba* may be made to represent the secondary copper loss, at the input corresponding to the ordinate *Id*. The secondary current at this load (reduced to the primary circuit) is represented by the vector I_0I. This is permissible since the primary current *OI* may be considered as consisting of two parts; magnetizing component OI_0 and the other component I_0I, which produces ampere-turns equal and opposite to the secondary ampere-turns. Thus, we have to prove that *ab* is proportional to $\overline{I_0I}^2 \times r_2$, where r_2 is the secondary resistance of the motor, also reduced to primary terms (§ 500).

The triangles II_0c and II_0K being similar, we have that I_0c is equal to $\overline{II_0}^2 \div I_0K$. Thus, the loss in question is proportional to the segment I_0c. Now, by drawing any two lines such as I_0I_s and I_0g, radiating from the point I_0, it will be seen that the segment *ab* which these lines cut from the ordinate *Id* is proportional to I_0c. Therefore, the secondary copper loss may be represented by *ab*, provided the rays I_0I_s and I_0g are properly selected.

The primary copper loss $i_1^2r_1$ cannot be represented with exactness in a similar simple way; it may be shown, however, that it can be represented with sufficient accuracy by the segment *bc*. Namely, assuming the triangle OII_0 to be *approximately* a right-angle one, we have

$$i_1^2 = i_2^2 + i_0^2.$$

Multiplying this expression by r_1 we get that the primary copper loss $i_1^2 r_1$ may be approximately represented by

$$i_2^2 r_1 + i_0^2 r_1.$$

We have already seen that $i_0^2 r_1$, being the primary copper loss at no load, is already taken into account as a part of the ordinate *cd*. The other term, $i_2^2 r_1$, has the same form as the secondary copper loss, except that r_1 is substituted for r_2. Thus it can also be represented as a segment, such as *bc*, cut off from the input *Id* by two lines radiating from the point I_0.

The proper position of the line $I_0 g$ is found from the fact, that the whole input, with the armature locked, is converted into losses, since no useful work is performed by the motor under these conditions. The distance between the lines $I_0 K$ and Ox, accounts for iron loss, friction, and the copper loss corresponding to the no-load component of the primary current; consequently, the ordinate $I_s f$ must account for the secondary copper loss and the primary copper loss corresponding to the component $I_0 I_s$ of the primary current.

The expression $\overline{I_0 I_s}^2 \times r_1$ is calculated first, and plotted to the suitable scale as the ordinate *fg*; the rest, gI_s, represents the secondary copper loss with the armature locked. In motors provided with a squirrel-cage secondary this loss cannot very well be determined experimentally, or calculated directly.

Thus, by drawing the lines $I_0 I_s$ and $I_0 g$, all the losses in the motor may be separated, and the output calculated, corresponding to a given input.*

604. Output and Torque. — The ordinate *Id* representing the true input into the motor, and *da* being the sum total of the losses, the difference of the two, or *Ia*, represents *the output of the motor, in amperes.* Multiplying it by the voltage and dividing by 746 the output in horsepower is found.

The ordinate *Ib* is a sum of the output and the secondary copper loss, hence it represents working amperes input into the secondary: It is proportional to the energy transmitted from the primary into the secondary circuit, through the mechanical torque existing between

* The circle diagram, explained here, is accurate in all respects, except in the part where the primary ohmic loss is accounted for. In motors above 1 or 2 horsepower, the primary copper loss is usually so small in itself, that some inaccuracy in its value does not appreciably alter the results. With very small motors it is preferable to obtain performance curves directly from a brake test, the more that it can be performed much easier than with larger motors. Another alternative is to use more complicated diagrams, for instance such as described by Mr. Specht in the *Electrical World*, 1905, p. 388. See also Arnold's *Wechselstromtechnik*, Vol. V, part 1.

these two parts of the motor. Therefore, Ib represents the torque of the motor. To obtain the torque in foot-pounds, Ib is multiplied by the voltage, then by $33000/(746 \times 2\pi) = 7.04$, and is divided by the *synchronous* speed of the motor, in r.p.m. Synchronous speed should be taken in this case, and not the actual speed, because the diagram is constructed from the standpoint of the primary part of the motor. The torque is considered here as the input into the secondary, produced by a revolving magnetic flux which rotates synchronously.

Up to this time, the vectors, such as OI, Id, etc., have been supposed to represent currents in amperes, and to be converted into watts by being multiplied by the voltage of the supply. Instead of multiplying each separate ordinate, it is more convenient to change the scale of the

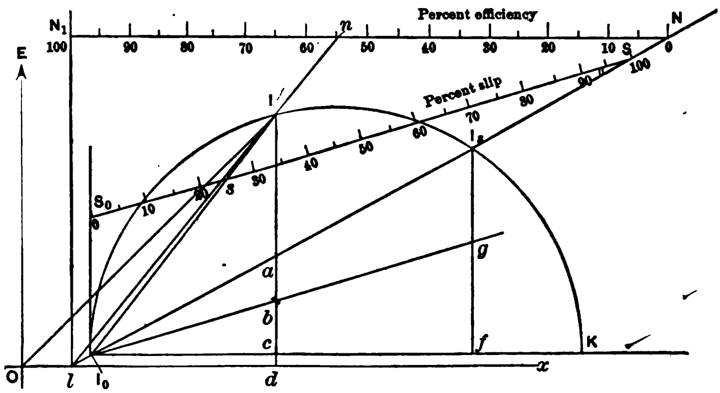


FIG. 444. Determination of efficiency and slip from the circle diagram.

circle so as to obtain vectors directly in watts, instead of amperes. Then the input Id, the output Ia, and all the losses may also be read in watts. If it is desired to express the input and the output in horse-power, instead of watts, the scale for the circle may be selected so that the ordinates will read directly in horse-power. This latter method for constructing the circle diagram is adopted in the instructions given in § 608 below.

605. Efficiency Scale. — Efficiency may be determined from the circle diagram (Fig. 443) as a ratio of the output Ia to the input Id. Some prefer to read the efficiency directly from the diagram, without taking the ratio. This is done by drawing an efficiency scale NN_1 (Fig. 444). Produce the line I_0I_s to the intersection with the axis Ox at the point l, and draw the vertical line lN_1. The efficiency scale NN_1 is a horizontal line drawn at any desired distance from the axis of abscissæ, and is only limited by the condition that its zero N should

lie on the line I_0I_s, and the point N_1, corresponding to 100 per cent efficiency, must be on the same vertical with the point l. To find the efficiency corresponding to a certain input Id, connect l to I and produce lI to its intersection with the efficiency scale at n. Nn gives the efficiency directly in per cent, while nN_1 represents the total losses, also in per cent of the input.

The proof of this construction is as follows: The triangles lNN_1 and lad are similar, therefore

$$ad \div ld = lN_1 \div N_1N.$$

The triangles lnN_1 and lId are also similar, so that we have

$$Id \div ld = lN_1 \div nN_1.$$

Dividing the first expression by the second, we obtain

$$ad \div Id = nN_1 \div N_1N,$$

or, in words,

$$\text{total losses} \div \text{input} = nN_1 \div 100.$$

This shows that nN_1 represents per cent losses; the rest, Nn, evidently represents the per cent efficiency.

606. Slip Scale. — It is pointed out in § 344 that in polyphase induction motors, per cent slip is equal to per cent secondary copper loss. This loss is represented in the diagram (Fig. 444) by ab; the input into the secondary is equal to Ib. Consequently, the slip of the motor at this particular load is equal to per cent ratio of ab to Ib.

Instead of figuring out the values of this ratio for various loads, it is convenient to have a scale on which per cent slip can be read off directly as is explained above for the efficiency.

Any line parallel to I_0g, such as S_0S, may be used as a slip scale, provided its zero point lies on the same vertical with the point I_0, and the division corresponding to 100 per cent slip is on the line I_0I_s. For any load, such as Id, produce I_0I to its intersection with the slip scale at s. S_0s reads slip directly in per cent; the remainder, sS, gives the actual speed of the motor, in per cent of synchronous speed.

The proof of this construction is as follows: The triangles I_0SS_0 and I_0ab are similar, so that

$$ab \div I_0b = I_0S_0 \div S_0S.$$

The triangles I_0sS_0 and I_0Ib are also similar; consequently,

$$Ib \div I_0b = I_0S_0 \div S_0s.$$

Dividing the first expression by the second, we obtain

$$ab \div Ib = S_0s \div S_0S,$$

or, in words,

$$\text{secondary copper loss} \div \text{input into the secondary} = S_0s \div 100,$$

which proves the construction.

607. Maximum Input, Maximum Output, etc. — The circle diagram (Fig. 444) gives directly the points at which various performance values obtain their maximum:

(1) Maximum input corresponds to the point at which the tangent to the circle is parallel to the axis Ox.

(2) Maximum torque corresponds to the point at which the tangent to the circle is parallel to the line I_0g.

(3) Maximum output corresponds to the point at which the tangent to the circle is parallel to the line I_0I_s.

(4) Maximum efficiency corresponds to the point at which the tangent from l touches the circle.

(5) Maximum power factor corresponds to the point at which the tangent from O touches the circle.

In plotting the performance curves from the diagram it is well to have all these points of maximum marked first, as they add considerably to the accuracy of the curves.

608. Instructions for Constructing a Circle Diagram. — The following instructions are given in order to enable the student to construct quickly and without hesitation a circle diagram (Figs. 443 and 444) from the results of a test, and to plot the corresponding performance curves, shown in Fig. 271. The instructions are given for three-phase motors, and the points of difference for two-phase motors are indicated.

(1) *Experimental Data.* The following data must be obtained experimentally, as is explained in §§ 610 to 612: Total no-load watts W_0, no-load amperes i_0 (per phase); total watts W_s with the armature locked (short-circuit watts), short-circuit current i_s (per phase). All of the above at the rated terminal voltage E of the motor. Resistance R (average) of the stator between two terminals.

(2) *Power Factor Quadrant.* Select, on a sheet of cross-section paper, convenient reference axes Ox and OE (Fig. 443). Take Op equal to 100 per cent power factor to a convenient scale; the scale should be preferably the same as used for plotting the power-factor curve on the curve sheet (Fig. 271). With Op as a radius strike the quadrant prq. For any vector of primary current, such as OI, the power factor is represented by the ordinate Ot of the point r, at which this vector intersects the quadrant.

(3) *Input.* Figure out the apparent horse-power input with the armature locked, $i_sE\sqrt{3} \div 746$ h.p., and plot it to a convenient scale as the vector OI_s, at a power factor $= 100\ W_s \div i_sE\sqrt{3}$ per cent. In the same way, plot the apparent horse-power input at no load, $OI_0 = i_0E\sqrt{3} \div 746$ h.p., the power factor being $100\ W_0 \div i_0E\sqrt{3}$ per cent.

Through I_0 and I_s draw a semicircle KI_sI_0, having its center on the horizontal line I_0K, passing through the point I_0. For any point, such as I, the vector OI represents the apparent horse-power input, the ordinate Id measures to the same scale true horse-power input. Maximum input which the motor can take corresponds to the point at which the tangent to the circle is parallel to the axis Ox. It is advisable to select the same scale for horse-power, that will be used on the curve sheet: the ordinates can then be transferred directly, without having them scaled off.

For two-phase motors substitute in the above formulæ the coefficient 2 in place of $\sqrt{3}$.

(4) *Primary Current.* The vector of the primary current coincides with the vector OI of apparent input. If OI is measured in horse-power, the primary current per phase $i_1 = 746 OI \div E\sqrt{3}$ amperes. For two-phase motors substitute 2 in place of $\sqrt{3}$.

(5) *Output.* Connect I_0 with I_s. Now Ia measures the output in horse-power, to the same scale to which Id measures the input. Maximum output corresponds to the point on the circle, at which the tangent to the circle is parallel to I_0I_s. To find the point corresponding to the *rated* output of the motor, draw a line parallel to I_0I_s, at a vertical distance from it, equal to this horse-power. This line will intersect the circle in two points; the point to the left is the one required, since it corresponds to a higher power factor and a higher efficiency.

(6) *Torque.* Figure out the expression

$$3 \times \left(i_s \frac{I_0I_s}{OI_s}\right)^2 \times \tfrac{1}{2}R \div 746 = \text{h.p. loss.}$$

(reduced primary copper loss with the armature locked), plot it to the horse-power scale as fg, and draw I_0g. For any input, such as Id, the ordinate Ib measures torque in *synchronous* horse-power.

$$\text{Torque in ft. lbs.} = \frac{\text{torque in synchron. h.p.} \times 5252.}{\text{synchron. rev. per min.}}$$

The maximum or the pull-out torque corresponds to the point, at which the tangent to the circle is parallel to I_0g. For two-phase motors use in the above formula the coefficient 2 instead of 3, and R instead of $\frac{1}{2}R$.

(7) *True Efficiency.* The true efficiency of the motor is equal to the ratio of Ia to Id. If it is desired to measure the efficiency directly, produce I_0I_s to l (Fig. 444) and draw the vertical line lN_1. The efficiency scale NN_1 is then drawn at such a distance from the axis Ox as to get the length NN_1 conveniently divisible by 100. It is best to

341
329
332
12

use for NN_1 the same scale which is intended to be used for efficiency on the curve sheet. To get the efficiency corresponding to the input Id lay a straight edge between the points l and I: the efficiency is read directly in per cent at the point n on the same line.

(8) *Apparent Efficiency* is calculated as the ratio of Ia to IO.

(9) *Slip.* Per cent slip may be calculated as the ratio of ab to Ib. If it is desired to read the slip directly, draw the vertical line I_0S_0 (Fig. 444) and a slip scale S_0S, parallel to I_0g. Select the distance at which the slip scale is drawn such as to have S_0S conveniently divisible into 100 parts. Or else, select S_0S equal to the synchronous revolutions per minute of the motor, to the scale used for the speed curve on the curve sheet. To find the slip for a point, such as I, lay a straight edge between the points I_0 and I: S_0s measures the slip, and sS the actual speed of the motor, either in per cent of the synchronous speed, or in actual revolutions per minute.

(10) *Plotting Curves.* Select on the circle several points such as I and mark the corresponding horse-power output as abscissæ on the curve sheet (Fig. 271). For each point, I, measure on the diagram: power factor, true and apparent input, torque, efficiency, slip and speed as explained above, transferring the lengths directly to the curve sheet. Determine also from the diagram the points of maximum input, maximum output, maximum power factor and maximum efficiency. Mark all these points on the curve sheet and then draw the curves.

609. Test Data for Predetermination of Performance. — In explaining the construction of the circle diagram, it was stated that the data, necessary for predetermining the performance curves of an induction motor, are:

(1) Ampere and watt input with the motor running idle.

(2) The same with the armature locked.

(3) Resistance of the stator winding.

It may seem at first that these tests, together with the necessity of constructing a diagram, and other calculations, should take more time than an ordinary brake test. Experience shows, however, that better results are obtained by the indirect method, even with less experienced observers, than is possible with a brake test. It is easier to perform a few simple runs in succession, than one complicated test.

The tests for obtaining the above data will now be described in detail; explicit instructions for constructing the diagram are given in the preceding article.

610. EXPERIMENT 29-A. — Measuring Resistances of Induction Motor Windings. — This experiment, with the two following, is

intended to supply data necessary for the predetermination of performance of the induction motor by means of the circle diagram (§ 608). Aside from this, the resistance may be measured for some other purpose, for instance, in connection with a heat run, or as a check on the construction of the motor. The resistance of the stator windings of an induction motor is usually measured by the drop-of-potential method. Direct current is applied between pairs of terminals of the motor in succession, and volts and amperes are read. Then the current is changed and the readings are taken again. It is advisable to have at least six sets of readings for each pair of terminals. Insert a thermometer into the winding so as to know the temperature to which the calculated resistance refers.

Report. If the motor is Y-connected, a resistance measured between two terminals corresponds to two phases in series, and should be divided by 2 in order to get the resistance of one phase. It is customary to first get the averages of all the readings between a certain pair of terminals, and then calculate the resistance per phase from these averages. If only the average resistance per phase is required, the three averages are added together and the result divided by 6.

If, however, a fault in the winding is suspected, or for any other reason it is desired to know the resistance of each particular phase, the problem is reduced to three equations with three unknown quantities:

$$x + y = R_{1-2},$$
$$x + z = R_{1-3},$$
$$y + z = R_{2-3};$$

from these equations the individual phase resistances x, y, and z can be easily determined.

It is left to the student to prove that resistances can be determined in the same way when the motor is Δ-connected, so that *in performing the test it is not necessary to ascertain the character of connections in the motor.*

A good way to get an average resistance from several readings of volts and amperes, is to plot volts to amperes as abscissæ and through the points thus obtained to draw a straight line passing through the origin. The trigonometrical tangent gives directly the value of the average resistance.

611. EXPERIMENT 29-B. — No-Load Characteristics of an Induction Motor. — The purpose of this test is to determine watts and amperes taken by the induction motor at no load, the data to be used in the construction of the circle diagram, together with the data of the preceding and the following experiments.

Wire up the motor as for regular operation and have resistances or transformers with taps provided in the primary circuit, in order to vary the voltage at the motor terminals (Fig. 269). Have a voltmeter, an ammeter, and a wattmeter connected in the primary circuit through a polyphase board (§ 49), in order to be able to use these instruments in all the phases in succession.

In measuring the power input by the two-wattmeter method (§ 526) it must be remembered that the power factor at no load is usually below 50 per cent, so that the *difference* of two readings must be taken, instead of their *sum*.

Run the motor for some time to obtain steady conditions of friction and lubrication. Then raise the terminal voltage about 50 per cent above the rated: read volts, amperes, watts and speed, the latter merely as a check on the frequency. Reduce the terminal voltage in steps, taking similar readings. Go to the lowest limit of the voltage, at which the motor is capable of running.

Report. Plot no-load amperes per phase and total watts, to terminal volts as abscissæ. Mark the values at the rated voltage, these values to be used in constructing the circle diagram. Explain the peculiar shape of the curves at low voltages.

612. EXPERIMENT 29-C. — Short-Circuit Characteristics of an Induction Motor. — The purpose of this test is to determine watts and amperes taken by an induction motor with the armature locked, the data to be used in the construction of the circle diagram, together with the data of the two preceding experiments.

This test should be performed very carefully, because the current with the armature locked is several times larger than the rated current of the motor, especially in motors of considerable size. Here, as in the previous test, it is advisable to take complete curves of amperes and watts, by varying the applied voltage. Begin with the highest voltage that the armature can stand, while the motor is yet cold, and then rapidly take the readings, gradually reducing the voltage. In many cases it is impossible to get readings at the rated voltage, as the winding heats up too rapidly.* In such cases the readings are taken for lower voltages, and the curves *extrapolated* to the rated voltage, as is explained below. This is easily done because the curve of amperes is practically a straight line, and the curve of watts is a parabola.

In measuring watts be sure to mark on the data sheet whether the two readings are to be added or subtracted; in other words, whether

* Should the windings get very hot, run the motor for a time at no load, to cool them off by the draft of air produced.

the power factor is above or below 50 per cent (§ 527). An easy way to determine this is to let the motor run at no load and to connect the wattmeter so that the two readings are positive. If they remain positive with the armature locked, the power factor remained below 50 per cent. If it becomes necessary to reverse the connections in one of the phases, the power factor is above 50 per cent.

Report. Plot amperes per phase and total watts, to terminal volts as abscissæ. Mark the values corresponding to the rated voltage, these values to be used in constructing the circle diagram.

If it is impossible to get readings at the rated voltage, the curves must be extrapolated. The curve of the current is theoretically a straight line passing through the origin: in practice, it often has a small curvature near the origin, probably due to a peculiar condition in iron with very low saturation. These lower points should be left out of consideration and a straight line drawn through the other points; this line may not pass through the origin.

The curve of watts is theoretically a parabola:

$$\text{Watts} = CE^2,$$

where C is a constant. The easiest way to extrapolate this parabola is to figure out the working component of the current, since this component is proportional to the voltage:

$$\text{power component} = \frac{\text{Watts}}{E} = CE.$$

Plot this power component to volts as abscissæ; it will give an approximately straight line. Produce this line up to the rated voltage; the ordinates of this straight line, multiplied by the corresponding voltages, give the ordinates of the watt-curve.

613. First Proof of the Circle Diagram. — No proof was given in § 602 above for the statement that the locus of the primary current in an induction motor is a semicircle. Two proofs will be given now, one based on reducing the induction motor to an equivalent stationary transformer, the other on an analysis of magnetic fluxes in the motor.*

Instead of considering the rotor revolving and delivering mechanical power, it may be assumed as locked and loaded electrically on non-inductive external resistances. The same currents can be produced in the primary windings, by suitably varying the resistances, as if the rotor were revolving and were loaded mechanically.

* The author's experience is that either the first or the second proof appeals more to the reader, depending upon differences of temperament, and of preparation.

By stopping the motor, the secondary induced e.m.f. is increased $n_1 \div (n_1 - n_2)$ times, where n_1 is the synchronous speed of the motor, and n_2 is its actual speed: The revolving flux cuts the secondary conductors at a rate proportional to $(n_1 - n_2)$ when the rotor is revolving; with the armature locked the speed at which the conductors are cut by the flux is equal to n_1. The frequency of the secondary currents being thus greatly increased, the reactance of the secondary is thereby also increased the same number of times. By adding such an external resistance that the rotor resistance is increased $n_1 \div (n_1 - n_2)$ times, the same current and the same electrical relations are obtained in the secondary, as with the rotor revolving; consequently, the primary current will have the same value and the same power factor. Varying

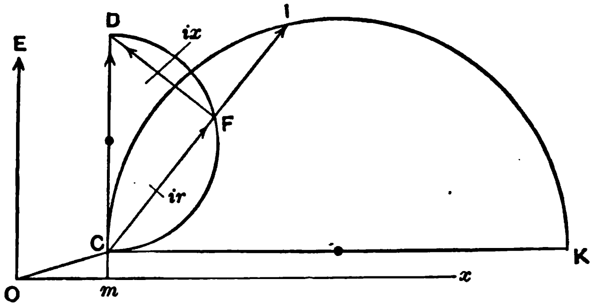


FIG. 445. First proof of the circle diagram: the induction motor is reduced to an equivalent transformer.

the external resistance is equivalent to varying a brake load with the armature revolving. In this way the induction motor is reduced to a stationary transformer, with an abnormal leakage and with a secondary load of non-inductive resistances, varying in value from zero to infinity.

Such a transformer can be replaced by an equivalent resistance and an equivalent reactance (see § 499), and the problem is reduced to merely this: *A non-inductive load is connected to a constant-potential line, with some resistance and some inductance in series with it* (Fig. 363). *The locus of the current vector when the load changes from zero to infinity is to be determined.* This problem is solved in Fig. 445. *CD* represents the vector of the line voltage, which is constant; *CI* is the current at a certain load. *CF*, in phase with the current, represents the resistance drop; *FD*, perpendicular to the current vector, represents the reactive drop. *CD*, the geometrical sum of *CF* and *FD*, is constant; as the latter two vectors are perpendicular to each other, the point *F* moves on the semicircle having *CD* for its diameter. The equivalent

reactance being constant under all conditions of load, the vector FD is proportional to the current, and represents it to a certain scale. Thus, it will be seen that when the load varies, the extremity of the vector of the current moves on a semicircle. This semicircle, CIK, has its diameter perpendicular to CD, because FD is perpendicular to the true position of the current vector.

The above proof applies to the induction motor, since it has been demonstrated before that the circuits in the two cases are electrically equivalent. The only difference is that, in addition to the load current CI, the induction motor takes a magnetizing current Om and a small

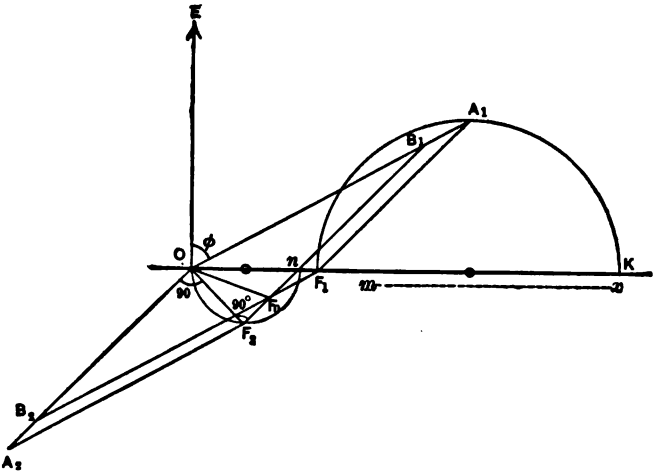


FIG. 446. Second proof of the circle diagram: relation between the primary and the secondary fluxes.

power component mC for overcoming iron loss and friction. This brings the total primary current to the value OI, and the diagrams, shown in Figs. 443 and 445, become identical.

614. Second Proof of the Circle Diagram. — The following proof is based directly upon a consideration of the magnetic fluxes, currents, and voltages in the motor. Let OE and OA_1 (Fig. 446) represent the applied voltage and the primary current in one of the phases. OA_1 also represents, to a certain scale, the primary ampere-turns, and, to another scale, the flux which these ampere-turns would produce if acting alone. Let OA_2 represent the same quantities for the rotor, *viz.*, the secondary current, ampere-turns, and the flux which the secondary winding would produce alone. The fluxes OA_1 and OA_2 are but fictitious, or component, fluxes of which the actual fluxes in the motor consist. Of the flux OA_2, only a part, say OB_2, links with the primary

iron; the rest, B_2A_2, links with the secondary winding alone, and constitutes the secondary leakage flux. Thus, the actual flux linking with the primary winding is the resultant OF_1 of OA_1 and OB_2. Similarly, only a part OB_1 of the fictitious primary flux OA_1 is linked with the secondary winding, the part B_1A_1 representing the primary leakage flux. Therefore, the actual secondary flux, OF_2, is the resultant of OA_2 and OB_1. The "transmitted" fluxes, OB_1 and OB_2, being superimposed, form the actual air-gap flux, OF_0.

The primary flux OF_1 is perpendicular to the vector of the voltage OE (neglecting small ohmic drop in the primary winding). The secondary current OA_2 is in phase with the secondary induced e.m.f., and is, therefore, perpendicular to the secondary flux OF_2, which produces this e.m.f. The applied voltage OE being constant, the primary flux OF_1 is also constant under all conditions of the load. The segment On is also constant, being a definite part of OF_1. This is because the triangles OA_1F_1 and OB_1n are similar, and the leakage ratio, B_1A_1 to OA_1, remains constant under all conditions of load.

Thus we have two conditions: (1) OF_2 is perpendicular to OA_2, or, which is equivalent, perpendicular to F_2B_1. (2) On is constant under all conditions of load. From these two conditions follows directly that, when the load varies, the point F_2 moves on the semicircle having On for its diameter.

It can be shown that the point A_1 also moves on the semicircle. The secondary current OA_2 is not only perpendicular to OF_2, but is also proportional to its value, because the flux OF_2 induces the secondary e.m.f. The segment F_1A_1 is parallel and proportional to OA_2 and consequently is perpendicular and proportional to OF_2. Therefore, when OF_2 describes a semicircle, F_1A_1 also describes a similar semicircle; in other words, the point A_1 moves on the semicircle F_1A_1K.

But A_1 is the extremity of the vector of the primary current OA_1, and we thus arrive at the proof that the locus of the extremity of the current vector is a semicircle. To make the diagram Fig. 446 identical with that in Fig. 443, the origin O must be shifted down to the line mx, in order to account for iron loss and friction, proportional to mI_0.

615. Predetermination of Performance of Single-Phase Induction Motors. — Theory and experiment show that the locus of the primary current for the single-phase induction motor is a semicircle, as for the polyphase induction motor, so that the predetermination of its performance by means of a circle diagram is possible. However, the relations in the diagram are somewhat different from those deduced

above, and the scope of use of single-phase motors does not warrant a detailed description of the corresponding diagram here. Moreover, single-phase induction motors are built in small sizes only, and there is no difficulty in obtaining the performance characteristics, either from a direct brake test or from the losses.

For performance diagrams of single-phase induction motors see Dr. McAllister's *Alternating-Current Motors*, B. A. Behrend's *The Induction Motor*, and Arnold's *Wechselstromtechnik*, Vol. V, part 1.

2. STUDY OF THE REVOLVING MAGNETIC FIELD.

616. It has been the experience of the writer that the average electrical engineer has a rather indefinite idea concerning the rotating magnetic field, *as a physical phenomenon.* This lack of knowledge in turn makes difficult an understanding of the theory and design of alternating-current machinery: the mathematical relations found in books often seem arbitrary and not sufficiently real; nor does the engineer see his way clear for original research in this branch of electrical engineering. It is with the view of giving a clearer *experimental* foundation for the knowledge of the revolving magnetic field that the following experiments are arranged. They are not regular commercial tests, but rather experimental demonstrations of the validity of the assumptions, made in practice, in regard to revolving magnetic flux.

617. Component Fluxes and Resultant Flux. — An elementary explanation is given in § 332 of how a *revolving* magnetic field is produced by a combination of two or more *pulsating* fluxes displaced in phase both geometrically and electrically. We shall now give the numerical relations between the values of the component fluxes and the intensity of the resultant flux, produced by three-phase currents.

Suppose the *maximum* magnetic density produced in the air-gap by the current *in one phase* to be B (Fig. 447); the density at a certain point, having the abscissa x, and at a time t is then

$$B \text{ Sin } mt \text{ Cos } x,$$

assuming the flux to be distributed *in space* according to the sine wave, and also varying *with the time* according to the same law. The density produced at the same point and at the same time by the second phase is

$$B \text{ Sin}\left(mt - \frac{2\pi}{3}\right) \text{Cos}\left(\frac{2\pi}{3} - x\right),$$

and that produced by the third phase:

$$B \text{ Sin}\left(mt + \frac{2\pi}{3}\right) \text{Cos}\left(\frac{2\pi}{3} + x\right).$$

Adding these three expressions, in order to get the resultant flux density, when all three currents are acting simultaneously, we get, after suitable mathematical transformations:

$$1.5\ B \operatorname{Sin}\ (mt - x).$$

This result being interpreted means that the maximum density, produced by the three phases, is only 50 per cent higher than that produced by each phase separately. Moreover, it means that this resultant maximum density *travels* along the air-gap at the angular velocity m, being distributed in space at any moment according to the sine law. The practical importance of this result is that in figuring out the magnetic flux of an induction motor with a given excitation, or vice versa, the calculations may be reduced to one phase by the above factor 1.5.

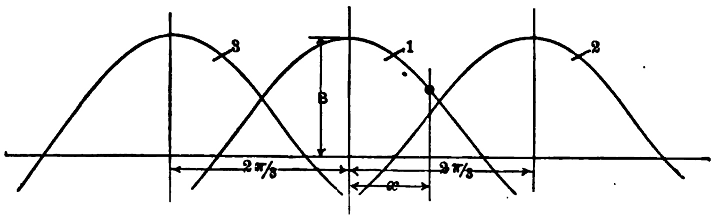


FIG. 447. Magnetic fluxes produced by three phases in the air-gap of an induction motor.

The factor 1.5 is correct only with sine-wave distribution of currents and fluxes. Factors differing from 1.5 are sometimes used in designing induction motors, and it is claimed that they represent more closely the actual form of the field, as influenced by the distribution of the winding. It has been shown experimentally, however, that the actual revolving flux follows quite closely the sine-wave law, with practically any distribution of windings. The reason probably is that higher harmonics are suppressed by the damping effect of the secondary winding.

618. EXPERIMENT 29-D. — Study of the Revolving Magnetic Field Produced by Alternating Currents. — The purpose of the experiment is to observe the relations explained in the preceding article. In order to simplify the measurements, the rotor should be taken out and a plain laminated iron core put in its place: the same offers a closed path to the lines of force, without influencing the field by induced secondary currents. If such a core is not available, the regular squirrel-cage rotor can be used, with one of the end-rings removed, so as to have the secondary circuit open. If the motor has a phase-wound secondary, the circuit is simply opened at the slip rings. In all cases the rotor is kept stationary during the experiment.

An exploring coil of a width corresponding to the pole pitch is placed on the secondary, and is connected to a suitable alternating-current voltmeter. Single-phase or polyphase currents are sent through the primary winding of the motor, and the magnetic flux in the air-gap is studied by measuring the voltage induced in the exploring coil.

(1) Excite one phase of the stator, between a terminal and the neutral point, by a single-phase alternating current, and investigate the magnetic field thus produced, by changing the position of the rotor, step by step, and measuring the induced secondary volts. It will be found, that the induced voltage is a maximum, when the secondary coil is held opposite one of the primary coils, and is zero in the position between two stator coils. It varies gradually in intermediate positions, as it should with the distribution of the flux, shown in Figs. 447 and 264–265.

(2) Repeat the same experiment with two phases in series (a double number of slots per pole).

(3) Change the connections between the coils so as to get half the number of poles, and again investigate the field.

(4) Now excite all three phases by three-phase currents, so as to produce a revolving magnetic field. It will be found, that the voltage induced in the exploring coil is practically constant in all positions. The explanation of this is, that the same field, traveling along the air-gap, will always cut the exploring coil, wherever it is placed. It will also be found that the induced voltage is not three times larger than that induced by one phase, but only about 50 per cent larger. This is due to the maxima of the magnetizing current in the three phases not occurring simultaneously, as is shown in the preceding article.

(5) In order to see more clearly that a *revolving* magnetic flux is actually produced, the central core is taken out, and a light pivoted piece of soft iron put in its place. It will be found, that this piece of iron will tend to revolve, attracted by the flux. Instead of soft iron, a copper or aluminum cylinder can be used; eddy currents induced in it by the revolving flux will be sufficient to set it in rotation. Reversing two primary leads reverses the direction of rotation of the magnetic field, and consequently that of the armature. In performing this last experiment the student must be careful not to overload the primary winding: the motor takes much more current when the central iron core is taken out.

Report. Plot curves showing the form of the single-phase field with one phase excited, and with two phases in series. Explain the difference in its shape and magnitude by constructing the theoretical form of the field. Give the ratio obtained between the values of single-

phase field and three-phase field; if it should be much different from the theoretical ratio 1.5, explain the cause.

619. The Determination of the Instantaneous Values of a Revolving Flux. — The preceding experiment gives only general information concerning the revolving field. If a more detailed investigation is desired, it becomes necessary to "stop" the alternating currents at a certain instant, or fix them at certain instantaneous values, until the form of the field is investigated by means of an exploring coil. Then another set of instantaneous values may be taken, the corresponding field explored, etc. This is conveniently done by means of a direct current, instead of alternating: the values of the currents in the three stator windings are adjusted to correspond to some three instantaneous values of a three-phase combination. The flux will be the same, as is produced instantaneously by the alternating currents, with an advantage that it can be kept at this value indefinitely, until the distribution of the magnetic field has been properly investigated.

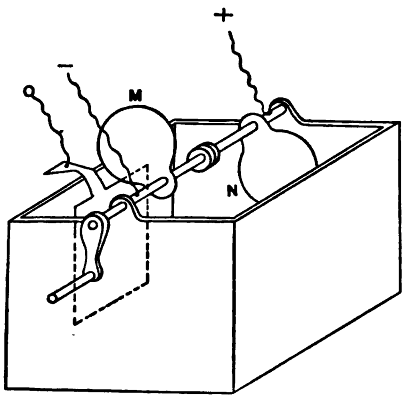


FIG. 448. A device for producing sinusoidal currents from a direct-current three-wire supply.

The exploring coil must be made very narrow so as to measure the field at a given point only; the coil is connected to a ballistic galvanometer, or a fluxmeter, instead of to a voltmeter (see §§ 119 and 120). The field is measured by placing the coil in a desired place in the air-gap, and then suddenly pulling it out. Instead of the coil being pulled out of the field, the main circuit can be opened, with the same effect on the galvanometer; the deflection is, in both cases, proportional to the flux. If the constant of the galvanometer is known, not only the relative distribution of the flux, but its absolute value can also be determined.

In order to more easily obtain any three values of direct current, corresponding to some instantaneous values of three-phase currents, a special liquid rheostat may be used, shown in Figs. 448 and 449. It consists of three glass jars A, B, C, such as are used for storage batteries, one for each phase. Each jar has two iron or nickel electrodes M, N, mounted on a shaft and insulated from each other. One electrode or blade is connected to the positive, the other to the negative pole of a three-wire direct-current supply. The liquid itself is connected to the

neutral wire of the supply, through the winding in which it is desired to regulate the current. According to whether the positive or the negative blade dips into the liquid, the current flows through the winding in one or the other direction. The strength of the current depends on the amount of immersed surface of the blade; by giving the blades a suitable shape, a current is produced, varying nearly as a sine wave, when the handle is uniformly rotated. Three such rheostats are combined, as shown in Fig. 449, with the three pairs of blades set at 120 degrees apart: Regular low-frequency three-phase currents are thereby produced in the stator winding. The apparatus can be stopped in any desired position for studying an instantaneous value and distribution of the field.

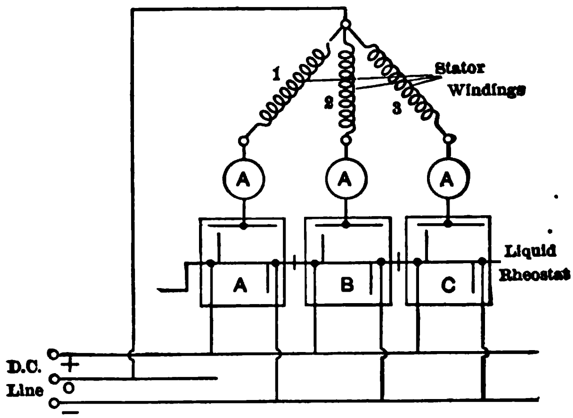


FIG. 449. Three-phase rheostat for a study of the revolving field in an induction motor.

If such a special rheostat is not available, three ordinary wire rheostats can be used, and the current in each phase adjusted separately. A table may be made, giving the instantaneous values of three sinusoidal currents, say, every 10 or 15 degrees.

620. EXPERIMENT 29-E. — Exploring Induction-Motor Field with Direct Current. — The purpose of the experiment is to obtain the actual form of the magnetic field in the air-gap of an induction motor. In order to observe the instantaneous values of the field, the stator is excited with direct current, and the intensity of the field is measured with a ballistic galvanometer or a fluxmeter, as explained in § 619. First explore the field with but one phase excited; then connect two phases in series, so as to have a different disposition of the single-

phase winding. Use a narrow exploring coil connected to a ballistic galvanometer, and, keeping the current constant, move the coil through 360 *electrical* degrees, taking discharges through the galvanometer every 5 or 10 degrees, by opening the circuit. Take an extra curve with a large exciting current, in order to see if a high degree of saturation in iron appreciably changes the field curve. Galvanometer deflections, plotted to the angular positions of the exploring coil as abscissæ, give a curve of the relative distribution of the magnetic flux in the air-gap.

After this, investigate the field with all the three phases excited through the above-described liquid rheostat. Take the first curve with such a position of the blades that the current in one of the phases is a maximum. Then gradually change the position of the blades by steps of 10 or 20 degrees until a position is reached in which the current is a maximum in another phase. Take a galvanometer reading with each position of the blades and read the corresponding currents in the three phases. The results plotted in the form of curves give a clear view of the field *traveling* along the air-gap.

An oscillograph, or the point-to-point method (see Chapter XXXI) may be used in this study, in place of the tedious process of exploring the field by a ballistic galvanometer. The particular arrangement can be easily devised by a person familiar with the use of wave-tracing devices.

Report. Give a sketch of the arrangement of the winding in the slots; plot curves of the single-phase field with one phase, and with two phases excited in series. Check the form of the field from the number of slots per phase and the disposition of the winding. Give curves showing actual currents in the three phases, to the angular positions of the blades as abscissæ. Plot curves showing the progression of the three-phase field in the air-gap. See if the form of the three-phase field can be predetermined from the shape of the single-phase field.

621. Magnetic Field in the Single-Phase Induction Motor.—When a single-phase induction motor (§ 346) is stationary, but is connected to the line, its field is merely pulsating, as in a transformer. When the motor is revolving, two kinds of secondary currents are induced in the rotor: (1) by the "transformer" action of the pulsating primary field, and (2) because of the secondary conductors cutting the lines of force of the primary field (generator action). These latter currents produce a field displaced by 90 electrical degrees in space from the primary field, and also displaced by 90 degrees in phase relation. The "generator action" currents, and consequently the "perpendicular" field, are proportional to the speed of the motor. This field is of zero

value at standstill, and gradually increases to a value nearly equal to that of the primary field as the motor gains in speed.

The result is that the single-phase induction motor has a nearly uniform *revolving* field at synchronous speed, while the field is only a pulsating one at standstill. At intermediate speeds an irregular elliptical field is produced.

The existence of the perpendicular field, produced by the armature currents, and its variation with the speed, are important features in the theory of the single-phase induction motor; it is therefore interesting to explore this field experimentally. When the motor has an auxiliary phase, as in Fig. 278, or when a two-phase or a three-phase motor is used running single-phase (Fig. 279), the investigation is made by measuring the e.m.f. induced in the idle phase, as is explained below.

622. EXPERIMENT 29-F. — Exploring the Field of a Single-Phase Induction Motor. —The purpose of the experiment is explained in the preceding paragraph. The main phase of the motor is connected to the line — if necessary, through a suitable resistance, or an auto-transformer, to reduce the voltage. The rotor is driven by some outside power, in order to maintain a desired speed. An alternating-current voltmeter is connected across the auxiliary phase: its indications are proportional to the "perpendicular" field.

It will be found that the voltage induced in the auxiliary phase gradually increases from zero, practically to that across the main phase, as the speed increases from zero to synchronism. This, of course, presupposes, that both windings have the same number of turns; otherwise the voltages must be reduced to an equal number of turns.

Measure volts, amperes, speed and power factor in the main phase. In order to determine the phase angle between the primary and the secondary flux, connect the main phase at one point to the auxiliary phase: Read the volts across each phase separately and then across the two phases in series, so as to get a triangle of voltages. With the arrangement shown in Fig. 279 the auxiliary phase is already connected at O to the main phase, so that the phase relations may be determined without any additional connection.

Report. Plot all observed values to speed as abscissæ. Construct a triangle of voltages for some speed near synchronism; from the power factor in the main phase determine the actual phase angle between the primary and secondary field; this angle must be nearly 90 degrees. In drawing conclusions take into consideration the difference in the number of turns primary and secondary, and the distribution of the winding in the slots (breadth factor).

CHAPTER XXX.

ARMATURE WINDINGS.

623. It has been customary heretofore to study armature windings by means of diagrams and sketches; it is much more profitable, however, to study them on models, by actually putting dummy coils in slots. This chapter is devoted to such a study, the exercises in winding being supposed to be performed in the laboratory.

The alternating-current windings, being simpler than the direct-current windings, are taken up first.

I. ALTERNATING-CURRENT WINDINGS.*

624. The simplest single-phase armature winding is shown in Fig. 249; it consists of conductors 1, 2, 3, etc., placed in the slots of a laminated-iron armature core (not shown) and connected in series by the end connectors C, C. The distance between the conductors is equal

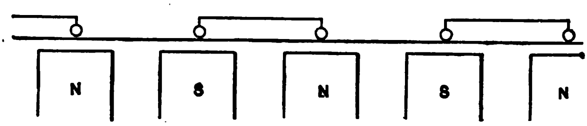


FIG. 450. A single-phase winding with one slot per pole.

to that between the centers of the consecutive poles, N, S, N, S, . . . of the machine, so that the conductors are subjected simultaneously to the action of the magnetic flux, and the e.m.f.'s induced in all of them are added together.

In the relative position of the armature winding and the poles, shown in Fig. 249, the induced e.m.f. is a maximum, since the conductors are in the densest part of the magnetic field. In the position shown in Fig. 250 the total induced e.m.f. is zero, because the conductors do not cut any lines of force; this position differs by 90 *electrical* † degrees from that in Fig. 249. In a position differing by 180 electrical degrees from that in Fig. 249 the conductor arrives at the center line of the pole S, and the induced e.m.f. becomes a maximum in the opposite direction (one alterna-

* For a more comprehensive treatment see Kinzbrunner's *Alternating-Current Windings*.

† In a two-pole machine this corresponds also to 90 *geometrical* degrees.

tion). When the next N-pole is reached, a complete cycle of alternating current has been accomplished.

The same winding is shown in Fig. 450: the small circles represent the conductors in the armature slots, and the lines between them the end connections. In many machines more than one slot is used per pole; with two slots per pole, the winding has the aspect shown in Fig. 451 or in Fig. 452. Both schemes are electrically equivalent.

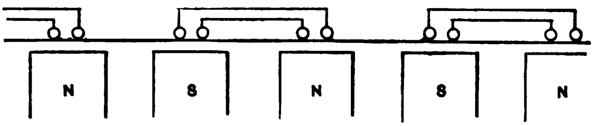


FIG. 451. A single-phase winding with two slots per pole.

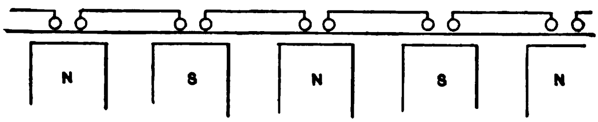


FIG. 452. Another arrangement of free ends of coils for the winding shown in Fig. 451.

Polyphase windings are formed by providing the same armature core with two or three independent single-phase windings in the right

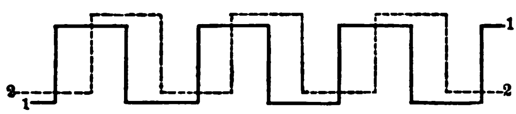


FIG. 453. A two-phase winding.

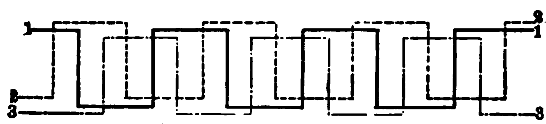


FIG. 454. A three-phase winding.

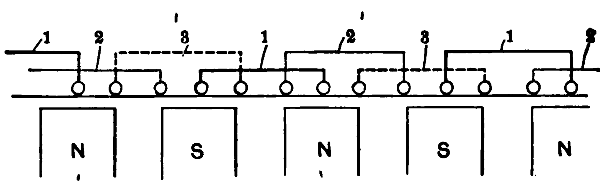


FIG. 455. Overlapping of free ends of coils in a three-phase winding.

positions relative to one another. A two-phase winding is shown in Fig. 453. It consists of two windings identical with those in Fig. 450,

and displaced by 90 electrical degrees. When the e.m.f. in one of the windings reaches its maximum, the e.m.f. in the other winding is zero, and vice versa. Fig. 454 represents a three-phase winding; it consists of three single-phase windings displaced by 120 electrical degrees with respect to one another. The separate phases are marked by 1, 2, and 3. The same winding is shown in Fig. 455.

Alternating-current windings used in practice are a development of these simple schemes and can be easily deduced therefrom.

625. Bar Winding and Coil Winding. — Low-tension alternators require a comparatively small number of conductors of a large cross-section; high-tension machines must have a large number of conductors of a comparatively small cross-section. Therefore, windings in low-tension machines are often made of insulated copper bars with soldered cross-connections at the ends (Fig. 456). In high-tension machines the number of bars in series becomes so large that it is necessary to use regular coils, consisting of many turns of wire (Fig. 457). Coil windings and bar windings offer some distinctive features, and will therefore be considered separately. It must be remembered, however, that the distinction is merely of a mechanical and geometrical nature. From an electrical standpoint, the two types of winding are equivalent. A certain number of conductors must be placed on the armature and connected in series, in order to produce a given e.m.f.; it does not make any difference whether they are formed as separate bars or bunched in coils.

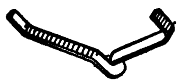


FIG. 456. The shape of end connectors.

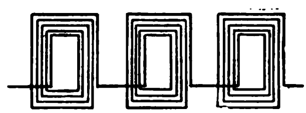


FIG. 457. Connections between the coils belonging to the same phase.

There are two distinct types of coil winding, chain winding, Fig. 460, and double-layer winding, Fig. 461. Both types may be used with the machines having open slots; the coils are machine-wound and are placed directly into the slots. With half-closed slots, chain winding only is used; the methods of placing the winding into the slots are described in § 630 below.

626. Experimental Frame. — A stator frame (dummy) should be provided in the laboratory, for the convenient study of alternating-current windings. Such a frame may be made from boards glued together and turned true on the inside. The teeth are formed separately, as a molding, and nailed to the frame, leaving spaces for the slots. Grooves should be left in the teeth for driving in wooden wedges to hold the coils in place.

Wooden bars may be used instead of metal conductors; cross-connectors (Fig. 456) should be preferably made of metal and fitted into slots made at the ends of the bars. For exercises in chain winding, regular coils should be used, or colored cord, which the student may wind into the slots of the frame. Coils for double-layer winding, Fig. 468, should preferably be obtained from manufacturers.

It is convenient to have a frame with a number of slots such as 72 or 96, which is divisible by several numbers, so as to be able to use various numbers of poles.

627. Form of Induced E.M.F. — The wave form of an induced e.m.f. depends on the number of slots per pole per phase, and on the arc subtended by the pole-pieces. To find the theoretical wave form in a given machine, imagine the poles moving and note the

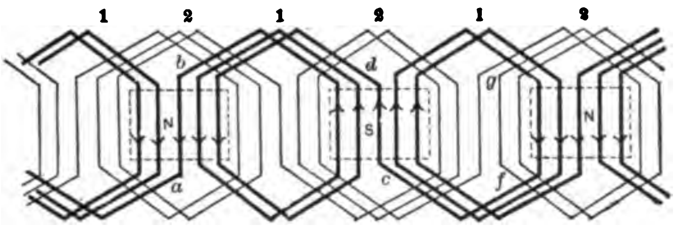


FIG. 458. A two-phase bar winding with five slots per pole per phase.

instantaneous e.m.f.'s induced in a group of coils. Thus, in Fig. 450 the e.m.f. is zero so long as a pole is between two conductors. When the edge of the pole comes opposite a conductor, the e.m.f. suddenly reaches its maximum value, and remains constant until the other edge of the pole passes by the conductor. In reality, the e.m.f.-curve is not altogether flat, but has rounded corners, due to a "fringing" of the magnetic flux around the poles.

With two slots per pole per phase (Fig. 451), first one slot comes under the influence of the pole, and then two, so that the curve of the induced e.m.f. has an intermediate step. With three slots per pole per phase the induced e.m.f. is practically a sine wave.

Having an actual alternator, it is possible to compare the theoretical wave form with that actually observed, by the methods described in Chapter XXXI. By connecting two phases of a three-phase machine in series, and using it as a single-phase machine, a winding is obtained having a double number of slots per pole per phase; this is a simple method of investigating the influence of the number of slots on the wave form of the induced e.m.f.

628. Bar Winding. — A standard two-phase bar winding with five conductors per phase per pole is shown in Fig. 458; conductors belonging to one phase (No. 1) are indicated by heavier lines. The five conductors under one pole are placed in 5 slots; this gives a good e.m.f. wave-form, and considerably reduces the armature inductance. By following the connections, it will be seen that all the conductors of the same phase are connected in series, so that the e.m.f.'s induced in them are added, and do not counteract each other. It will also be seen that three sizes of bars are necessary with this kind of winding: Long bars, such as *ab*, for passing from one coil to the next one; short bars, such as *cd*, for the same purpose; and medium bars, such as *fg*, inside of each coil. The cross-connectors have the form shown in Fig. 467, so that by having long and short ends on each side of the core it

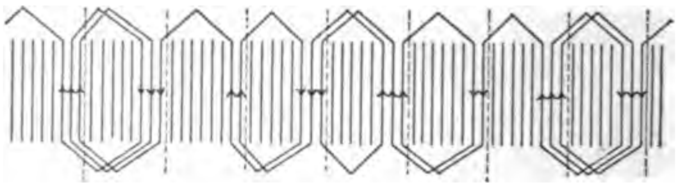


FIG. 459. An unsymmetrical three-phase winding, eight slots per pole.

is possible to make the connections shown in Fig. 458, without the cross-connectors touching one another. A similar type of winding can be used for three-phase machines.

In some cases it is convenient to use a standard frame for a special machine, and it may occur that the number of slots is indivisible by the number of poles, or by the number of phases required with this special machine. The frame can nevertheless be used by allowing a somewhat unsymmetrical winding. Suppose, for instance, that a manufacturing company is regularly using a 96-slot frame for 16-pole three-phase alternators of a certain size; this corresponds to 6 slots per pole, or 2 slots per pole per phase. Suppose that for some reason a customer desires to have a machine with a somewhat higher speed, say, such that it becomes necessary to use only 12 poles, instead of 16, in order to keep the same frequency. This means 8 slots per pole, a number indivisible by the number of phases. The problem is solved as shown in Fig. 459. Three bars are used for two consecutive poles, and only two bars for each third pole. No trouble is experienced in operation with such an apparently unsymmetrical winding.

Another alternative in such a case is to have the machine wound for *T*-connection (Fig. 417). With 8 slots per pole, the phase-winding

AB is placed in 4 slots and the winding *CD* in 4 slots. A part of the latter winding is left idle, a tap being taken at 86.6 per cent of it. This arrangement is particularly convenient when a machine must generate, according to circumstances, either two-phase or three-phase currents, for instance in supplying currents for testing purposes.

629. EXPERIMENT 30-A. — Exercises with Alternating-Current Bar Windings. — An experimental frame should be provided for this exercise, as described in § 626. Select a number of poles possible with the number of slots of the frame and place a single-phase winding, using three different lengths of bars, as in Fig. 458; have them properly cross-connected. Take a few other combinations possible with two-phase and three-phase machines, and place a sufficient number of bars in the slots, to show clearly the disposition of cross-connectors. Finally select a number of poles such as to get an unsymmetrical winding, shown in Fig. 459.

Report. Give diagrams of windings investigated during the experiment; make a table of all the combinations and numbers of poles possible with a given frame. Show by an example how to determine the theoretical wave form of the induced e.m.f. from the disposition of the winding (§ 627). For the wave form thus obtained determine the ratios of the effective value and of the average value to the maximum ordinate. Assume for the same example a certain magnetic flux per pole, and calculate the voltage of the machine, at a speed corresponding to a standard frequency. Take the flux such as to get in the teeth a density of about 90,000 magnetic lines per square inch. Assume that about 65 per cent of the periphery is covered by the poles, and allow a reasonable amount for fringing.

630. Chain Winding. — The chain winding consists of separate coils, and is shown in Fig. 246 in application to a three-phase machine. Fig. 451 shows a similar winding with two slots per pole per phase, one phase only being indicated.

The coils belonging to the same phase are connected in series; sometimes the two groups of coils are connected in parallel in order to use the same winding with two different voltages.

Some of the coils with this type of winding have straight heads, others have their heads bent outward to avoid crossings; the idea is clearly seen in Fig. 460. Each coil has one head straight, the other bent. In some cases both heads of one coil are straight, those of the other bent, as is explained below.

Chain winding may be used with either open or half-closed slots. The advantages of half-closed slots are: (1) A lower flux density in

the air-gap and therefore less exciting ampere-turns; (2) A more uniform distribution of the magnetic flux in the air-gap; (3) A lower magnetic density in teeth, and therefore a smaller iron loss. On the other hand, the winding with half-closed slots is much more expensive, since it is more difficult to wind.

With open slots, coils are wound on special formers, or molds, on winding machines. Some coils are made with both heads bent, others with straight heads. The coils with bent heads are placed in the slots first, and then the coils with straight heads.

With half-closed slots there are three ways of winding:

(1) The coils are wound by hand in the slots, using suitable molds for the heads, and threading the wire to and fro. First the coils with bent heads are wound, and then the coils with straight heads over and between them.

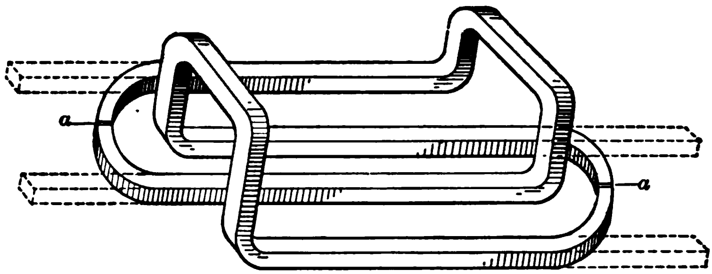


FIG. 460. **Relative position of coils, which are opened at *a* before being put into slots.**

(2) The coils are machine-wound and have the form shown in Fig. 460, one head being straight, the other bent. Before being put into the slots the coils are cut at the places marked *a*, *a*, and straightened out, as indicated by dotted lines. They are then shoved into the slots, the wires are bent back, soldered together, and carefully insulated turn by turn. This is such an expensive and tedious process that in many cases it is preferred to wind them in the slots by hand.

(3) The coils are machine-wound, but the wires are not bound or taped together. A coil is placed on the machine, and each side is threaded into the corresponding slots wire by wire. This winding is used in some common types of small induction motors (Fig. 267).

631. EXPERIMENT 30-B. — Exercises with Alternating-Current Chain Windings. — An experimental frame similar to the one described in § 626 should be used in this exercise; use form-wound coils and cord of three colors to distinguish the phases. The properties of

chain windings are explained in the preceding article. Select a suitable number of poles, place in the slots a single-phase winding, and properly interconnect the coils. Do the same with a two-phase and a three-phase winding, using in each case a different number of poles. Place a sufficient number of coils, in order to see clearly how the heads are interlinked. *Report:* Similar to that in § 629.

632. Double-Layer Winding. — The double-layer winding (Fig. 461) is used with open slots only, the coils being form-wound. The ends of the coils have the same form as in direct-current armatures (see Fig. 468).

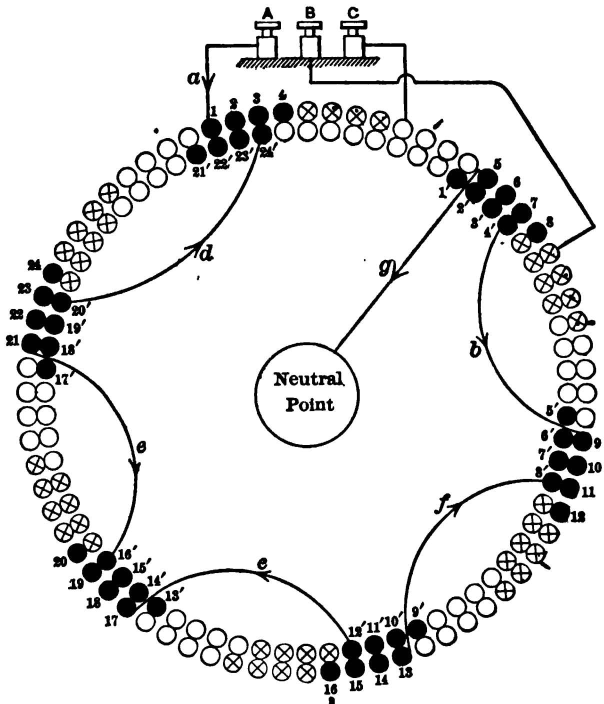


FIG. 461. Double-layer winding of a six-pole three-phase induction motor.

To make the winding symmetrical, one side of each coil is placed in the lower half of the slot, the other side in the upper half. Fig. 461 represents the disposition of coils in a six-pole three-phase stator with 72 slots (four slots per pole per phase). Conductors belonging to different phases are marked by different circles; the conductors in one of the phases are numbered, the two sides of each coil being denoted by the same number. The three phases are wound exactly alike. Therefore the cross-connections between the groups of coils are shown

in the sketch for one phase only, those in the two other phases being omitted for the sake of clearness. The four coils of each group, such

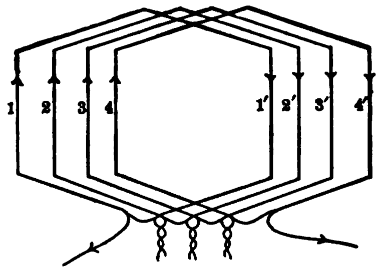


FIG. 462. Interconnection of coils belonging to the same pole and phase, in the winding shown in Fig. 461.

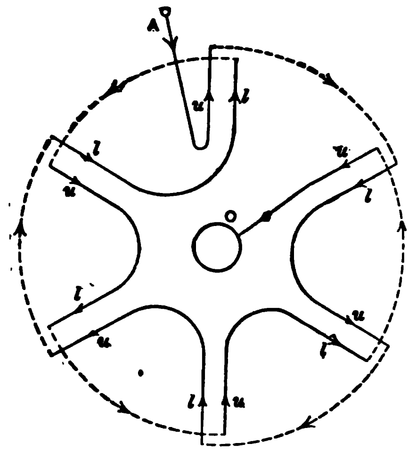


FIG. 463. Series connection of the groups of coils shown in Fig. 461.

as coils 1, 2, 3, 4, are connected in series, as shown in Fig. 462; then the separate groups are again connected in series, as per Fig. 463. In this diagram the conductors in top of the slots are denoted by u (upper), those in bottom by l (lower). The dotted lines connect the conductors belonging to the same coil; the inner curved lines represent the cross-connections between the groups of coils, just as in Fig. 461. By following the arrows, which indicate the directions of the induced e.m.f.'s, it is easy to see the necessity of arranging the connections as shown in Fig. 463, in order to have all the conductors in series.

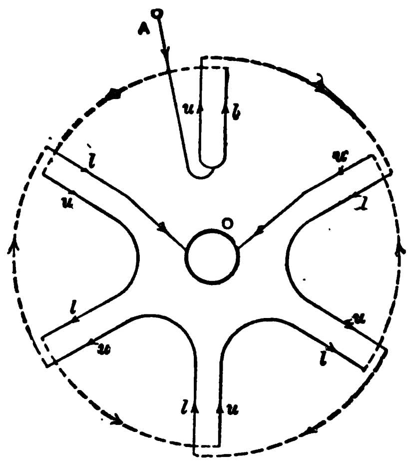


FIG. 464. Parallel connection of the groups of coils shown in Fig. 461.

Sometimes the same frame and the same winding are used for 220-volt and 110-volt motors, the coils being connected in series for the higher voltage (Fig. 463) and in parallel for the lower voltage (Fig. 464).

633. EXPERIMENT 30-C. — Exercises with Alternating-Current Double-Layer Windings. — The properties of the winding are described in § 632. The directions for performing the experiment and the requirements for the report are similar to those in § 629.

2. DIRECT-CURRENT WINDINGS.*

634. The simplest type of a two-pole armature is shown in Fig. 465. A number of bars or coils are laid in the slots on the periphery of an armature core, and are interconnected so as to give a closed winding. The conductors are also connected to the commutator bars, from which the current is led to the external circuit. The connections satisfy two conditions:

(1) The winding constitutes a closed circuit in itself;

(2) The elements are so connected that the e.m.f.'s induced in them are added at all moments, and do not counteract each other.

The necessity of the second condition is self-evident. The first requirement is made clear in Fig. 466, namely, if the winding is closed on itself, it remains identical, relatively to the brushes, in all positions of the armature, so that the armature gives a direct, or *continuous*, current. It will also be seen that the armature is divided by the brushes into two parallel branches, each carrying one half of the total current.

635. Single-Layer Bipolar Winding. — Let us now follow in detail

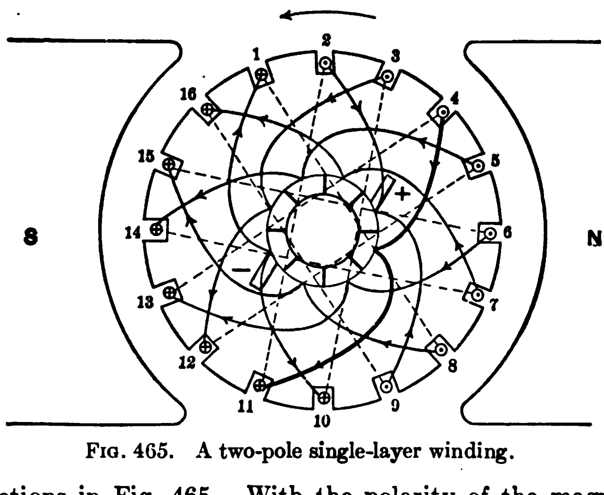


FIG. 465. A two-pole single-layer winding.

the connections in Fig. 465. With the polarity of the magnetic field and the direction of rotation shown there, we find by the familiar

* For a more comprehensive treatment see Kinzbrunner's *Continuous-Current Armatures.*

rule, that if the machine is acting as a generator the currents induced in the conductors under the *N*-pole are flowing toward the observer (up); in those under the *S*-pole—from the observer (down). This is indicated in the figure by dots and crosses within the conductors.

The whole winding must be symmetrical, that is, all connections must have the same "throw." The throw in the particular case shown is equal to 7, that is to say, the conductor 1 is connected to 8 and to 10, these being the 7th conductors on each side from 1; bar 2 is connected to 9 and 11, etc. The throw must be an odd number, in order that all the bars be connected before the winding is closed upon itself. Suppose we would take a throw equal to 6, and connect 1 to 7. Then from 7, keeping the same throw, we should get to 13, thence to 3, etc., closing the winding on *odd* bars only. The throw must be only slightly less than one half of the number of bars. Then one comes to the first bar only after having connected together all the bars on the armature. Moreover, in no place of the armature do induced e.m.f.'s counteract one another.

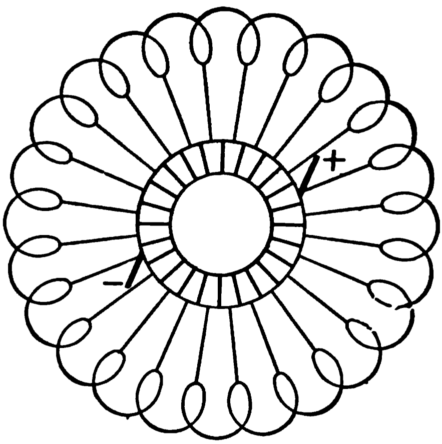


FIG. 466. Diagram showing that the armature winding is divided by the brushes into two parallel branches.

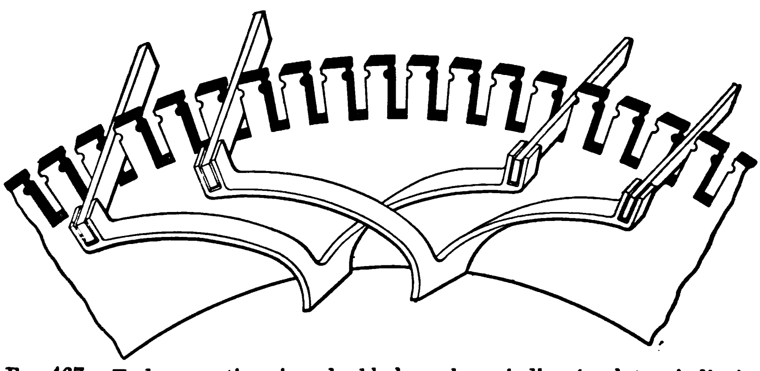


FIG. 467. End connections in a double-layer bar winding (evolute winding).

The path of the current in the armature is as follows: Current enters the armature through the negative brush and is divided into two parts,

one flowing to 1, the other to 10. Following the first half: The current flows "down" through 1 and returns "up" through 8, the connection between 1 and 8 being on the back of the armature, as indicated by dotted lines. From 8, it flows to 15, then to 6, etc., until it reaches the conductor 2, and leaves the winding through the positive brush. These connections can be represented thus:

neg. brush — 1—b—8—f—15—b—6—f—13—b—4—f—11—b—2—f — pos. brush.

The letters "b" and "f" stand for "back" and "front," indicating whether the connection is on the front or the back side of the armature. The course of current through the other half of the armature conductors can be followed in a similar way. As mentioned before, the two halves are put in parallel by the brushes.

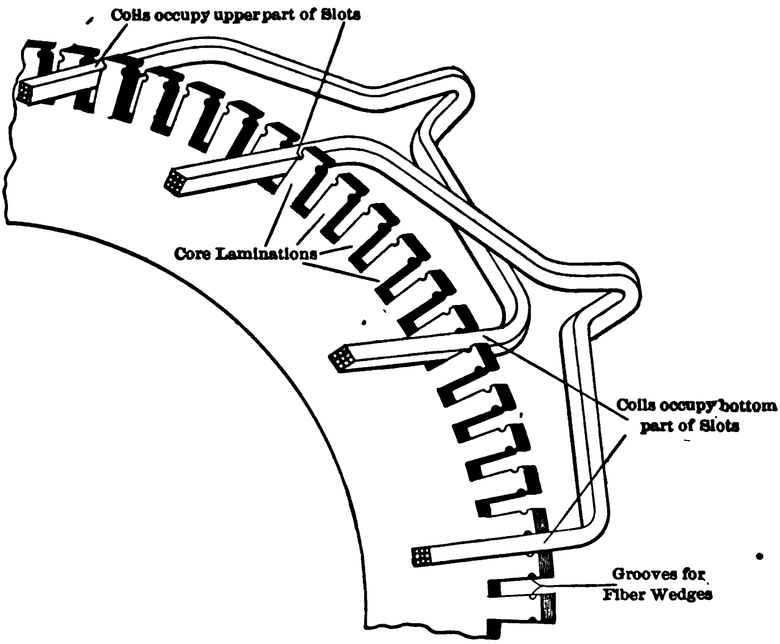


FIG. 468. End connections in a double-layer coil winding (barrel winding).

636. Double-Layer Bipolar Winding. — The above scheme (Fig. 465) presupposes that the conductors or the coils are placed in one layer. With modern slotted armatures the coils, as a rule, are put in two layers (Fig. 469), because this allows of a better utilization of the space available for the winding. In order to make all connections

identical, one side of each coil is placed in the bottom of the slot, the other side in the top (Figs. 467 and 468).

When the winding consists of copper bars (Fig. 467) the cross-connectors are placed in planes perpendicular to the bars. Such winding is sometimes called the *evolute winding*, because of the form of the cross-connectors.

With form-wound coils (Fig. 468), end connections are usually made along the cylindrical surface of the armature. Such a winding is sometimes referred to as the *barrel winding*. The general scheme of connections remains the same as in Fig. 465, only, instead of having all the conductors in one layer, each two adjacent conductors must be imagined as placed in the same slot one on top of the other; for instance, all odd conductors are in the bottom and all even ones in the top.

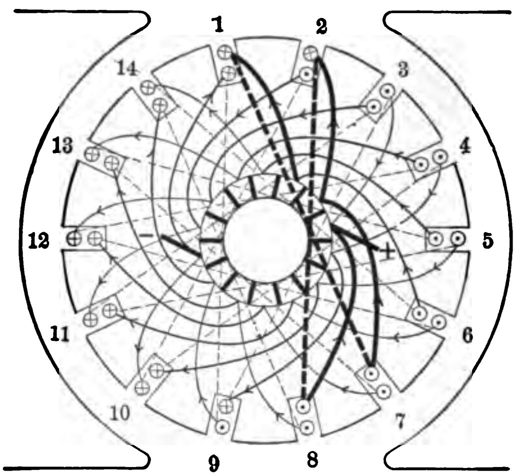


FIG. 469. A two-pole double-layer winding with an even number of slots.

Either an even or an odd number of slots can be used with double-layer bipolar windings (Figs. 469 and 470). Actual armatures, as a rule, have many more conductors or coils than is shown in these diagrams: Therefore, putting all the coils and connections on the drawing would make it rather too complicated. This is, however, not necessary, since all the coils are connected according to a certain "throw." In the winding departments of electric manufacturing companies, drawings are used, on which but a few conductors are shown and the throw is given. The winder places the first coils as shown in the drawing, and then keeps up the right throw until all the slots are

filled with coils. Then he drives in fiber wedges which hold the coils in place, and solders the connections.

637. EXPERIMENT 30-D. — Exercises with Direct-Current Bipolar Windings. — A wooden model of an armature is convenient for study of windings; it should be provided with regular teeth and slots. Ordinary cord may be used for winding, instead of wire; wooden bars with metal end-connectors are convenient for illustrating the winding shown in Fig. 467. Form-wound coils should be provided to demonstrate the barrel winding (Fig. 468).

(1) Wind into the slots a single-layer winding, shown in Fig. 465. First wind in place separate coils, such as are shown in slots 1 and 8, 2 and 11, etc., each coil consisting of several turns. Then properly cross-

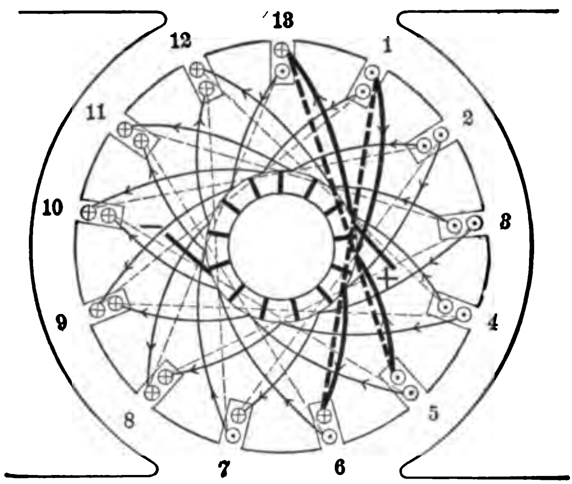


Fig. 470. A two-pole double-layer winding with an odd number of slots.

connect the ends of the coils, and make sure that the winding is entirely symmetrical and closed upon itself.

(2) Do the same with the double-layer windings shown in Figs. 469 and 470. If the number of slots of the model is even, a winding with an odd number of slots is realized by omitting a slot, as if it were not there.

(3) Place a few form-wound coils (Fig. 468) into the slots, and make clear to yourself the way they are designed, so as to avoid crossings, and to make the winding symmetrical all around. Try also the bar winding shown in Fig. 467.

638. Multipolar Windings. — In *multipolar* machines, currents of alternate direction are induced in groups of conductors under consecutive poles. The winding is arranged so that several groups are con-

nected either in series or in parallel. Accordingly, two types of windings are distinguished: *multiple* winding and *series* winding. The condition in Fig. 466, namely, that the winding must form a closed circuit divided by the brushes into two parallel branches, must always be fulfilled; even with the pure series winding there are always two circuits, each taking one half of the armature current (series winding is therefore sometimes called two-circuit winding). In multiple winding the number of branches in parallel is more than two. Fig. 471 gives a general scheme of connections for a multiple winding of a six-pole armature. There are six branches in parallel, and each coil carries but one sixth of the total line current.

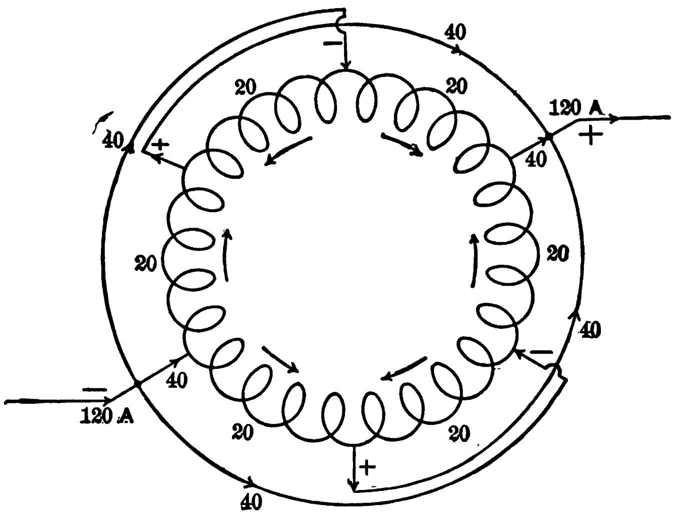


FIG. 471. Paths of current in a six-pole multiple-wound armature.

The selection of a series or a multiple winding in each particular case is substantially determined by the voltage and the current of the machine. Large currents should be avoided in armature conductors, as they necessitate heavy bars, difficult to handle and to insulate; moreover, the copper loss is considerably increased by eddy currents in the conductors themselves. In this case multiple winding should be used, as it considerably reduces the actual currents carried by the armature conductors (for instance, in a 12-pole machine, currents are reduced 12 times). On the other hand, in medium-size, low-speed, 500-volt generators, such as are used for direct connection to steam-engines, the principal difficulty is to get the required voltage, without making the machine too bulky and expensive. Here, as many conductors as

possible should be connected in series, and a two-circuit, or series winding is preferable. Series winding is also used in railway motors, as it enables them to have a counter-e.m.f. of 500 volts induced at a comparatively low speed.

With very large machines, say above 1000 kw., both difficulties arise at once: The currents are large enough to make necessary several branches in parallel, and at the same time the conductors under one pole are not sufficient to produce the required voltage, so that series

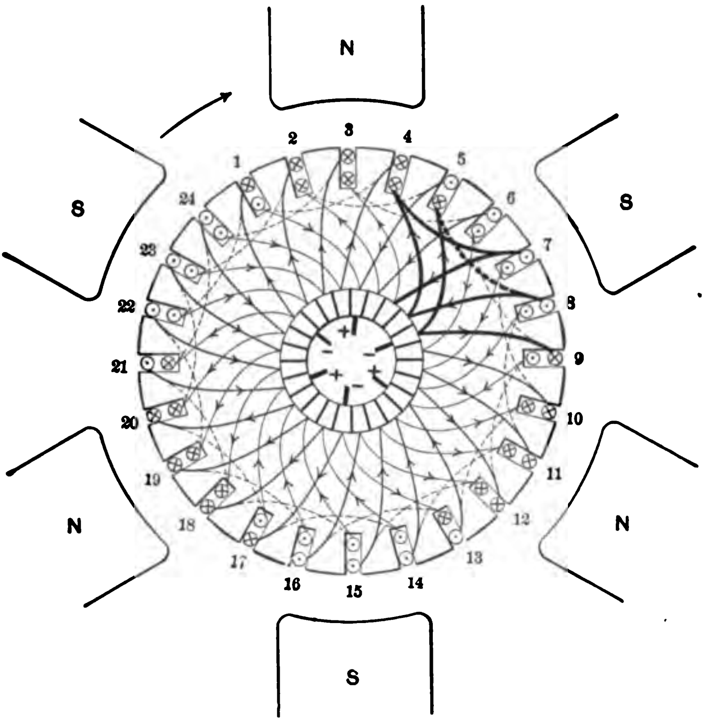


FIG. 472. A six-pole multiple-wound armature.

windings must be recurred to. To meet this case a combination *series-parallel winding* has been devised. For instance, instead of using an ordinary series winding on a 1500-ampere, 500-volt railway generator, three *separate* series windings are placed on the armature, each carrying 500 amperes. Each third consecutive commutator bar belongs to the same winding. The brushes cover more than three commutator segments, and thus connect the three windings in parallel with respect to the external circuit, while inside of the machine each winding is a two-circuit winding.

639. Multiple Windings. — Fig. 472 shows a six-pole *multiple winding* with two conductors per slot; a development of the winding is shown in Fig. 473, from which the origin of the name "*lap-winding*" can be seen. The winding in Fig. 472 is of the same character as that in Fig. 469 or 470, if the latter be imagined cut through in one place and spread over a large drum, so as to occupy on it only 120 degrees instead of 360 degrees. Three such windings put side by side give the six-pole winding of Fig. 472.

The number of slots in a two-pole winding can be either even or odd (Figs. 469 and 470). As a multiple winding is a combination of several two-pole windings put side by side, the number of slots in it can also be even or odd, but must be divisible by the number of pairs of poles. For instance, a six-pole machine may be wound with 39 slots, giving 13 slots per each pair cf poles. Strictly speaking, even this limitation is not absolutely necessary, and the armature may be provided with any number of slots. Under these conditions, however, the number of coils under separate poles is slightly different at different moments, which gives unbalanced induced e.m.f.'s; therefore such a disposition should be avoided.

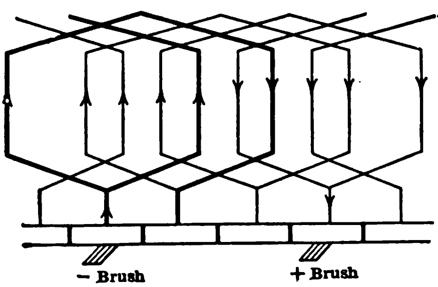


FIG. 473. Development of a multiple winding (lap winding).

The arrangement of coils is the same as in the corresponding two-pole winding. For instance, in the above example of a six-pole armature with 39 slots, the coils are placed in the slots 1 and 6, 2 and 7, etc., as in Fig. 438; this is a little less than the pole pitch. Such a "throw" insures that the e.m.f.'s induced on both sides of the coil are added, the two sides being under opposite poles. The winding is closed on itself after all the coils are properly interconnected.

640. Tables of Connections. — Windings may be conveniently represented by table instead of by sketches or diagrams. Thus the winding shown in Fig. 472 is represented by the following table:

+ brush — brush + brush

bottom of slot $1_0-2_1-3_3-4_5-5_6-6_5-7_3-8_1-9_0-10_1-11_3-$ etc.,
connected on the front;

outer part of slot $5_0-6_2-7_4-8_6-9_6-10_4-11_2-12_0-13_0-14_2-15_4-$ etc.,
connected on the back.

Large figures denote the conductors, small figures the induced voltages.

Leaving, for the time being, the voltages out of consideration, the table reads as follows: The conductor on the bottom of the slot 1 is connected on the back of the armature (dotted lines in Fig. 472) to the conductor on the outer part of the slot 5. This latter conductor is connected in front of the armature (on the commutator side) to the conductor on the bottom of the slot 2, etc. It will be easily seen that such a table gives the diagram of connections much clearer than a complicated sketch.

The numbers, indicating the voltages, explain the electrical character of connections. During the moment shown in the diagram, Fig. 472, the following slots are under the poles:

2, 3, 4, 6, 7, 8, 10, 11, 12, 14, 15, 16, etc.;

only in these conductors are e.m.f.'s induced. We assume arbitrarily that the potential of the conductor placed on the bottom of the slot 1, is = 0, and that 1 volt is induced in each conductor under the poles.

The next conductor 5 in the table has also potential zero, since 5 is not under any pole. The potentials of the next conductors are each one volt above that of the preceding conductor, because they are under the poles, and are connected in series. The potential rises up to the conductor 8 in the top row: this conductor has a potential of 6 volts above that of the first conductor. The potential remains the same under the conductors 5 and 9 which are not under the poles; then it gradually drops again to zero at the next neutral zone.

The brushes marked on the table are placed at the points of maximum and minimum potential. It will be seen that with a six-pole multiple winding, three positive and three negative brushes are necessary in order to collect currents from all the sections of the armature.

641. Short-Chord or Fractional-Pitch Winding. — The distance between the two sides of a coil, expressed in the number of slots, is called the "throw," or the coil-pitch. In the multiple windings described above, the throw is one slot (or one half slot) less than the pole pitch. It is possible to use coils with a smaller pitch than this: such windings are referred to as having a fractional pitch, or as short-chord windings.

Take, for instance, a 12-pole machine with 120 slots, or 10 slots per pole. The pole-pitch is 10, or from the slot 1 to the slot 11. The regular coil-pitch is one less, or from the slot 1 to the slot 10. A short-chord winding is obtained by placing the coil in the slots 1 and 9 instead, and even in the slots 1 and 8. The only condition is, that

the two sides of the coil should not come under the same pole; otherwise the induced e.m.f.'s would oppose each other, making the coil electrically ineffective.

The poles usually cover from 55 to 70 per cent of the periphery. Assume in the given case the poles to subtend, say, 60 per cent of the periphery. Then, with 10 slots per pole, the slots 1 and 8 can never be simultaneously under the same pole, so that the foregoing condition is fulfilled.

Fractional-pitch windings are used to a considerable extent; their advantages are:

(1) Shorter end-connections, therefore less copper and a higher efficiency.

(2) Armature reaction is reduced since the currents in the neutral zone flow partly in opposite directions, neutralizing each other.

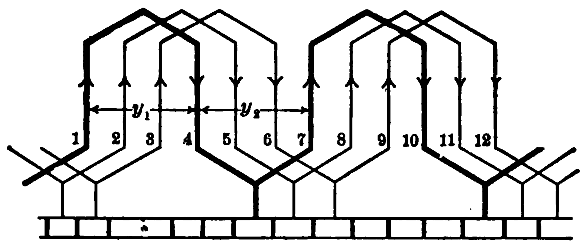


FIG. 474. Development of a two-circuit winding (wave winding).

It is recommended that the student work out a table for the above data, 120 slots, 10 poles, assuming first the throw to be equal to 9 (1–10), then equal to 7 (1–8); he should also draw a diagram similar to Fig. 472. The table will clearly show the difference between the full-pitch and the fractional-pitch windings. The diagram will explain why the armature reaction is reduced by selecting fractional-pitch windings.

642. EXPERIMENT 30-E. — Exercises with Direct-Current Multiple Windings. — The experiment is conducted on a wooden model in the same way as the experiment described in § 637. Wind coils of cord, using the type of winding shown in Figs. 472 and 473, with a full and a fractional pitch. Do this for two or three different numbers of poles, so as to become perfectly familiar with the winding. Place on the model a few machine-wound coils (Fig. 468) and bars (Fig. 467), and make clear to yourself the mechanical features of the winding, and the geometrical relations. Measure the diameter and the length of the armature core and the size of the slots.

Report. Give tables of the windings used (§ 640), for a full-pitch winding and for a short-chord winding. Make a sketch, as in Fig. 472, for one of the numbers of poles possible with the model. Draw, to scale, end connections for the types of winding shown in Figs. 467 and 468. The size of the coils and of the bars must be such as to fill the slots.

643. Series or Two-Circuit Winding. — The difference between the series and the above-described multiple windings can be seen by comparing Figs. 473 and 474. In Fig. 473 a conductor is connected to another one under the consecutive pole and then back to a conductor *under the same pole.* In this way the winding under each pair of poles constitutes a circuit by itself, and the separate circuits are put in parallel by the brushes. In the series winding, shown in Fig. 474, a conductor, such as 1, is connected in series with the similarly situated conductors, 4, 7, 10, etc., *under all the poles of the machine,* and only then to the conductor 3 under the same pole as 1. In this way the conductors of the armature are all connected into one circuit, which is divided by the brushes into two parallel branches. The shape of the winding in Fig. 474 justifies the name "*wave winding.*"

A simple six-pole wave winding is shown in Fig. 475. Only two brushes are necessary, although four or six may be used if large currents are to be collected. The winding is always placed in two layers, as in Figs. 470 and 472: a single-layer winding is shown merely for the sake of simplicity. One side of each coil lies on top of a slot, the other side lies on the bottom of another slot, under the next pole.

Let s be the total number of armature coils, p the number of pairs of poles ($p = 3$ for a 6-pole machine, $p = 4$ for an 8-pole machine, etc.), and y_1 and y_2 the throws on the back and the front side of the armature (Fig. 474). These throws are sometimes selected so as to differ in value from each other; the advantage of doing so is shown below. The condition must be fulfilled, that after having gone once around the armature, we return to the coil next to where we started. This is expressed by the equation

$$p\,(y_1 + y_2) = s \pm 1,$$

whence

$$y_1 + y_2 = \frac{s \pm 1}{p}.$$

If p is even (4-, 8-, 12-, etc., pole machines) the number of coils must be odd. If p is odd (6-, 10-, 14-, etc., pole machines) the number of coils s can be either odd or even. As an illustration, suppose that the number of conductors for a 10-pole machine ($p = 5$) is figured out to be about 500. Assuming the winding to be made of coils of two turns

each, the necessary number of coils is 125. From the above formula we see that the total number of coils s must be taken equal either to 124 or to 126: in both cases $y_1 + y_2 = 25$. Thus, we have to make $y_1 = 12$ and $y_2 = 13$, or vice versa; the throw is different on the back and on the front side. The value $s = 124$ gives the so-called *progressive* winding; $s = 126$, a *retrogressive* winding. If we should prefer to have $y_1 = y_2$, we should have to use either 119 or 121 coils, or else 129 or 131 coils.*

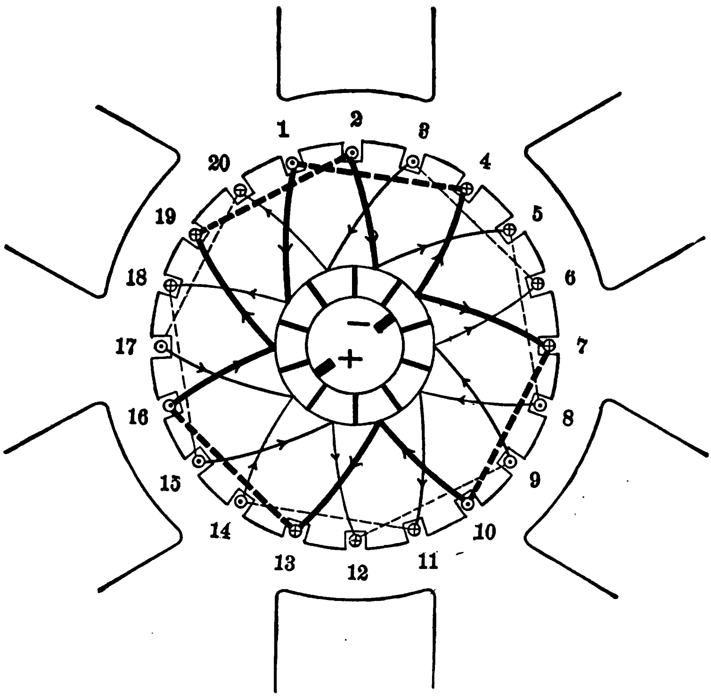


FIG. 475. A six-pole series-wound armature (single-layer).

It will be seen from the above that by making the two throws slightly different it is possible to have a larger number of possible solutions, with the same number of slots. This makes it possible not only to

* The term "coil" is used above to designate an element of winding, the two ends of which are connected to commutator segments. Two or more coils are frequently placed in one slot, side by side. Thus, in the example quoted above let 126 coils be selected. The number of slots can be either 126, or 63; in the latter case eight conductors are placed in one slot. With two poles, it is permissible to reduce the number of slots to 42, so as to use twelve conductors per slot.

design an armature closer to the results of calculation, but also to use the same armature punchings for more than one type of machine.

Tables of connections, explained in § 640 in application to multiple windings, are used equally well with two-circuit windings.

644. Use of an Idle Coil. — It sometimes happens that the punching selected for a special machine has a number of slots which does not satisfy the above formula for two-circuit windings. In such cases *an idle coil* is put in (Fig. 476), and the winding is completed in the usual manner. The idle coil gives the armature a symmetrical appearance and mechanical strength. If a standard commutator is used, there is also an extra commutator bar to which the idle coil must be connected on one side. If the commutator is made specially for the machine, with the right number of bars, the idle coil remains insulated on both ends.

In some four-pole railway-motors, even of a standard manufacture, an idle coil is not to be avoided. This is the case when, for some considerations, four coils are placed in one slot, two on the bottom and

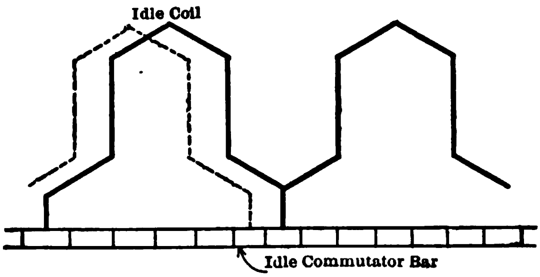


FIG. 476. The use of an idle coil.

two on the top, so that the total number of coils is even. It is explained above that in a four-pole machine a two-circuit winding is possible with an odd number of slots only. Therefore one coil remains idle and is insulated on both ends.

645. EXPERIMENT 30-F. — Exercises with Direct-Current Two-Circuit Windings. — The experiment is performed in the same way as those specified in §§ 637 and 642. On the model core place windings for two or three different numbers of poles, with equal and with different throws on the front and on the back of the armature. Place a winding with which an idle coil is necessary. Devise a double or a triple winding (series-parallel winding), as explained at the end of § 638. Use cord of different colors to distinguish the circuits.

CHAPTER XXXI.

ALTERNATING-CURRENT WAVE FORM.

646. IN a great majority of engineering calculations relating to alternating-current machinery and transmission lines, it is legitimate to assume voltages, currents, and magnetic fluxes, to vary according to the sine-law (Fig. 102). This assumption is justified, since the results of calculations come sufficiently close to the actual test data. At the same time, both the graphical and the analytical treatments of alternating-current problems are made much simpler than would be possible without the sine-wave assumption.

There are practical cases, however, in which the observed phenomena cannot be accounted for, by assuming a sine-wave distribution of currents and voltages, and where it becomes necessary, or at least desirable, to deal with the actual wave forms of alternating currents and voltages.

An experimental investigation of the wave form of alternating currents proves to be particularly helpful in the following subjects:

(1) In the study of commutation in direct- and alternating-current machinery.

(2) In investigations of electric disturbances taking place in cables, high-tension lines, etc.

(3) In research of phenomena taking place in the electric arc, rectifiers, etc.

(4) In telephonic research.

Moreover, a knowledge of the actual instantaneous phenomena in alternating-current circuits has contributed materially to the theory of protective apparatus.

In all these cases an experimental determination of the wave form has permitted the substitution of actual facts for a mass of speculative theories which had been advanced heretofore, because of the lack of experimental means for observing rapidly-varying irregular electrical phenomena.

Determination of the wave form of alternating currents is in some respects similar to taking indicator cards on steam- and gas-engines: Both give exact information about the actual working of a machine from moment to moment. Voltmeters and ammeters give only effective or average values for a certain length of time.

Two methods are used in practice for experimental determination of wave form of currents and voltages, the *point-to-point* or *contact-maker* method, and the *oscillograph* method.

I. POINT-TO-POINT METHOD.

647. The general principle of the point-to-point method is shown in Fig. 477. *NS* is the field and *A* the armature of an alternator, the wave form of which is to be determined. For simplicity, the machine is assumed to be of a two-pole, revolving-armature type. It has, in addition to two regular slip rings f_1, and f_2, a third ring or

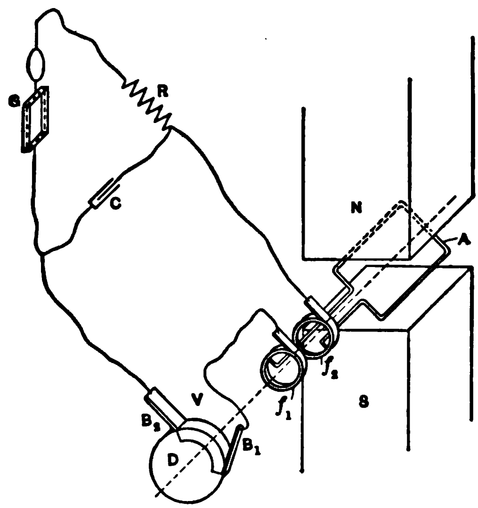


FIG. 477. The principle of determining an alternating-current wave form by the point-to-point method.

contact-maker *D* mounted on the same shaft, and revolving synchronously with the machine. The ring *D* is made of some insulating material, and has a metal segment *V* on a part of its periphery. Two brushes, B_1 and B_2, press against this ring, and are set at such an angular distance that the circuit is closed only during a very small part of a revolution. This is sufficient, however, to charge the condenser *C*: when the circuit is broken, *C* discharges through the galvanometer *G*. As these charges and discharges take place many times a second, the galvanometer assumes a steady deflection, proportional to the value of the individual discharges, in other words, proportional to the voltage at the condenser terminals.

This voltage depends on the position of the brushes B_1 and B_2. If they are set in such a position in regard to the alternator field, that

the circuit is closed when the induced e.m.f. of the machine is at its maximum, the voltage at the condenser terminals, and therefore the deflection of the galvanometer, have their largest values. If the brushes are set so that the circuit is closed when the induced e.m.f. passes through zero, the condenser receives no charge, and the galvanometer deflection is zero. In an intermediate position of the brushes, the deflection of the galvanometer is proportional to the instantaneous value of the voltage of the machine.

With this arrangement, the e.m.f. wave form of an alternator is taken by reading galvanometer deflections and shifting the brushes B_1 and B_2. The rocker arm, to which the brushes are fastened, is provided with an index, which slides along a circular scale divided into degrees. The brushes are shifted, say 5 degrees at a time, and the galvanometer deflection noted.

The results are plotted as in Fig. 486, giving galvanometer deflections against brush positions as abscissæ. The former are proportional to the instantaneous voltages, the latter correspond to the particular moments at which contact is closed. The curve thus plotted represents the actual wave form of the voltage of the machine. If the galvanometer constant is known, the curve may be plotted directly in volts; otherwise its effective value (square root of the mean square of the instantaneous values) is calculated and compared to the same value (voltage of the alternator) measured on the voltmeter. This gives the scale of the instantaneous values.

648. A Modification of the Point-to-Point Method. — The contact-maker D can be driven directly by the alternator in exceptional cases only, since the machine is usually not accessible. Therefore, the contact-maker is usually driven by a small synchronous motor connected to the same supply which is being investigated (Fig. 478). The speed being synchronous, this arrangement is equivalent to the one in which the contact-maker is driven directly from the alternator. The contact-maker K is somewhat different from that shown in Fig. 477, and the brushes are set side by side. The cross-hatched part is made of fiber, the remaining portion is of brass. Electrically the two arrangements are equivalent, since in both cases the current is closed for an instant during each revolution.

Another difference between the arrangements shown in Fig. 477 and in Fig. 478 is that, in the latter, instantaneous voltages are directly compared to an equivalent drop in a direct-current circuit, instead of being measured by galvanometer deflections. This does away with the galvanometer and the condenser, and makes possible the use of an ordinary direct-current voltmeter.

Referring to Fig. 478, the alternating voltage, whose wave form is to be determined, is taken from the terminals *A. C.* The circuit is closed through the contact-maker *K*, a double-throw switch *Sw.*, and a high resistance *GG*. This resistance is also connected to a direct-current supply *D. C.*, so that a constant direct-current circulates through it. By moving the contact *S* along the resistance, a position is found, in which the direct voltage is equal to the instantaneous value of the alternating voltage, given by the contact-maker. This voltage is then read directly on the voltmeter *V*.

The point of equilibrium is determined by means of a telephone receiver *T* connected into the alternating-current circuit. When the A. C. voltage does not balance the D. C. voltage, a clicking noise is heard in the telephone, corresponding to the frequency at which the

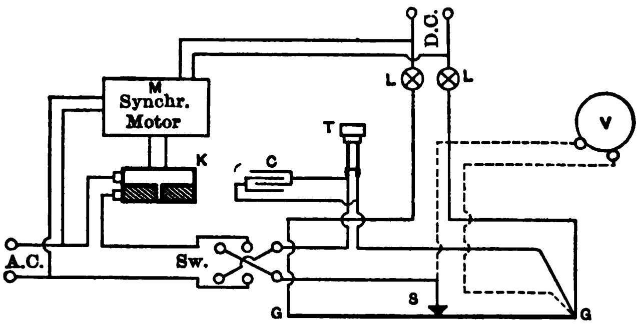


FIG. 478. The diagram of connections for balancing instantaneous values of alternating voltage by continuous voltage.

current is interrupted at the contact-maker. When the two voltages balance each other, the noise disappears. To increase the sensitiveness of the receiver, a condenser *C* can be connected across its terminals. A milli-voltmeter, or any zero-reading galvanoscope, may be used for balancing, instead of the telephone receiver.

M is a synchronous motor driving the contact-maker; its armature is connected to the A. C. supply, and the field is excited with direct current. The lamps *LL*, connected in series with the resistance *GG*, are useful as a precaution in case of a short-circuit. The double-throw switch *Sw.* is necessary in order to be able to take both halves of an alternating-voltage wave, with the same direction of the direct current in the resistance *GG*.

If it is desired to determine the wave form of an alternating *current* instead of *voltage*, the general scheme of connections remains practically the same; only the terminals A. C. must be taken in this case from the

ends of a non-inductive resistance connected in series with the circuit. With this arrangement, a voltage curve is taken at the terminals of this resistance, which curve has the same form as the current wave of the circuit. This procedure is analogous to using a milli-voltmeter with a shunt for measuring direct currents.

If it is desired to obtain the voltage and the current curves simultaneously, in their proper phase relation, suitable double-throw switches must be provided so as to change quickly and conveniently from one scheme to the other.

A disadvantage of the contact-maker K is that the contact lasts an appreciable time instead of being instantaneous; this is objectionable with complicated wave forms, since a considerable part of a higher harmonic may be comprised in the time of the contact. To obviate this, Professors Bedell and Ryan proposed to use a tiny stream of salt water which makes an instantaneous contact with a revolving pin. Another arrangement, proposed by Adams, is based on the use of a spring, which makes and breaks the contact in the same movement, almost instantaneously. These devices are described in detail on p. 188 of Swenson and Frankenfield's *Testing of Electromagnetic Machinery.*

649. EXPERIMENT 31-A. — Determination of Alternating-Current Wave Form with a Contact-Maker. — The purpose of the experiment is to afford familiarity with the use of the arrangement shown in Fig. 478 and to obtain curves of wave form in cases of practical importance. The synchronous motor M is started by means of an auxiliary direct-current motor, synchronized and switched on to the alternating-current supply.* Then the direct-current circuit is closed through the resistance GG. The terminals $A.C.$ are connected either across the line or across a non-inductive shunt in series with the line, according to whether the voltage or the current curve is to be taken. Then the contact S is shifted along GG until a position of silence in the telephone receiver is found. If a galvanoscope or a milli-voltmeter is used instead of the receiver, this corresponds to the zero position of the pointer. Then the voltage is read on the direct-current voltmeter V, it being at the same time the instantaneous value of the alternating voltage at the terminals $A.C.$ To get another point on the curve, the contact-maker brushes are shifted by a few degrees and the same measurements repeated. When zero point of the alternating wave is reached, the current must be reversed by means of the switch *Sw.*, and the second half-wave taken in the same way.

(*) A three-phase synchronous motor may be started directly from the alternating-current side, without excitation, as explained in § 587.

Care should be taken to keep currents and voltages constant during the whole test. If the A. C. voltage is too high to be compensated by the available D. C. voltage, a non-inductive resistance, say a few incandescent lamps, are connected across the supply, and the leads to the contact-maker are taken across a part of this resistance. Such, for instance, is the case when a curve is to be taken of a 110-volt supply, and the highest continuous voltage obtainable is also 110 volts. It is evident that the peak of the alternating curve is considerably above 110 volts, and could not be compensated on *GG*.

The following curves can be taken in the laboratory by this method:

(1) Current and voltage curves of the laboratory supply at a non-inductive load.

(2) Same, with a highly inductive load and approximately the same value of the current.

(3) The curve of the current taken by a large transformer at no load. The wave is considerably distorted because of the hysteresis phenomena in the iron.

(4) Current wave of an arc lamp, and a curve of potential difference between the carbons. Both curves have a somewhat peculiar shape, which can be explained by the fact that the arc is actually extinguished at each alternation, and the voltage has to attain a certain value before the current jumps between the carbons and starts the arc.

(5) If an experimental alternator is available, it may be of interest to take its voltage curve. Ripples similar to those in Fig. 479 will be clearly seen according to the number of teeth in the armature. These ripples constitute a higher harmonic, and in order to make them still more pronounced, some capacity is connected across the terminals of the machine, so as to produce a resonance effect.

(6) Curves of the current taken by a synchronous and an induction motor. These curves may, under certain circumstances, be considerably distorted, due to the counter-e.m.f. of the motor being of a different shape than the e.m.f. of the supply.

Have a wattmeter connected into the circuit in at least one of the above measurements, in order to compare the phase displacement actually measured by the contact-maker to that calculated from the power factor of the load.

The method itself may be learned in the taking of one curve; but the above six curves are suggested as possible exercises, and as many of them should be taken as time and laboratory facilities will permit. Moreover, the curves are of considerable practical importance, and it is interesting to take them for this reason.

Report. (1) Plot the curves obtained experimentally, and explain the irregularities, where possible. (2) Take one of the curves, figure out the effective value of the ordinates (root of mean square) and plot an equivalent sine wave; compare the effective value to that read on the alternating-current voltmeter. Determine also the ordinary mean value of the ordinates. (3) Calculate the ratios of the maximum value to the effective value and to the mean value; compare these ratios to those for the sine wave ($\sqrt{2}$ and $\frac{1}{2}\pi$). (4) Where the curves of voltage and current were taken simultaneously, check the phase displacement from the wattmeter reading. (5) Analyze at least one of the curves into its harmonics, as explained in § 659 below.

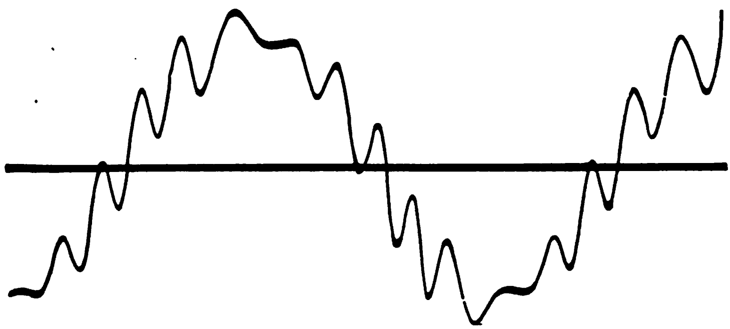


FIG. 479. Voltage curve with a prominent eleventh harmonic.

Separating the fundamental, the third, and the fifth harmonics is sufficient for the purpose, as this is merely intended to illustrate the method of analysis.

2. OSCILLOGRAPH.

650. The above-described contact-maker method has two good points in its favor: It gives fairly accurate results, and at the same time it does not require the use of special delicate devices. Its disadvantages are: Being a "point-to-point" method it is somewhat tedious; if the wave to be observed is not perfectly steady the curve obtained represents an average rather than the actual wave; the apparatus is not suited for observing rapidly-changing *non*-periodical phenomena, as, for instance, the effect of switching in or out of a long transmission line. The method is not suitable for high-frequency phenomena, because of the practical impossibility of driving the contact-maker at the required speed. For work of this kind so-called *oscillographs* are used, or instruments which give practically instantaneous wave records on a screen, or on a photographic plate.

In contra-distinction to the point-to-point method, the wave is here traced by a beam of light simultaneously with the actual changes in current: the result gives the image of an *individual* wave, instead of being an average of many impulses, as in the former method. A sample of such a curve, traced by a beam of light upon a photographic plate, is shown in Fig. 479. It represents a voltage curve actually observed on an alternator, running on unloaded cables with considerable electrostatic capacity; the eleventh harmonic is prominent.

The beam of light must be given simultaneously two movements: one along the axis of the ordinates, proportional to the instantaneous values of the current; the other — a uniform motion along the axis of abscissæ, proportional to time. These two movements, independent of each other, are produced in the oscillograph by different means, and will be described separately in the next two articles.

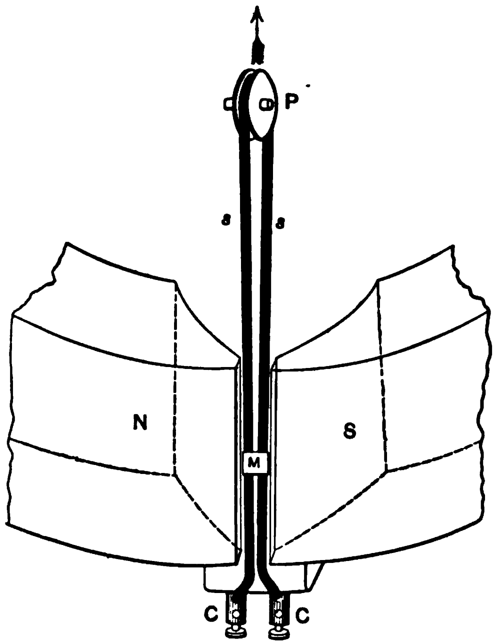


FIG. 480. The vibrating strips of the Duddell oscillograph.

651. Vibrations Proportional to Currents (Ordinates). — The principle of construction and operation of a practical oscillograph (Duddell's oscillograph) is shown in Fig. 480. In the narrow air-gap between the poles, *N*, *S*, of a powerful electromagnet, are stretched two parallel conductors, *s*, *s*, formed by bending a metal strip back on itself over the pulley *P*. A small mirror *M* is attached to the loop and serves the same purpose as a galvanometer mirror, viz., it indicates and magnifies deflections of the moving part by deflecting a ray of light. When a direct current is passing through the loop *s*, *s*, it causes one of the legs to advance and the other one to recede; the mirror is thus turned about a vertical axis. With a properly constructed instrument this deflection is made proportional to the current, so that the instrument is simply a sensitive moving-coil galvanometer. If the

current is variable, instantaneous deflections of the instrument are proportional to instantaneous values of the current: This is indicated by the beam of light, reflected from the mirror on a suitable screen. The only difference between this instrument and an ordinary galvanometer is that the moving system of the oscillograph is so light and has such a short period of natural vibration, that the mirror easily follows very quick variations of the current, which an ordinary galvanometer could not follow, because of its inertia. In the most accurate high-frequency oscillographs the natural period of vibration of the loop is in the neighborhood of one ten-thousandth of a second. The moving system is immersed in a viscuous oil, which has a damping effect, and prevents even these small vibrations from showing on the curve.

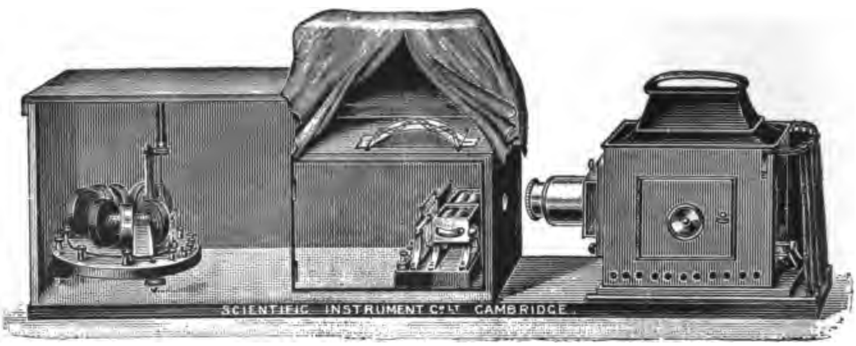


FIG. 481. The general arrangement of parts in a Duddell oscillograph with tracing desk.

With alternating currents traversing the loop s, s, the spot of light reflected from the mirror oscillates to and fro in a horizontal plane, as the current varies, and thus traces a straight line (ordinates). To obtain on the screen an image of the wave it is necessary to introduce the time element (abscissæ), as is explained below.

652. Movement Proportional to Time (Abscissæ). — Two distinct methods are used in the above oscillograph for producing a motion proportional to time, along the axis of abscissæ: (*a*) moving photographic plate or film, and (*b*) revolving mirror.

(*a*) *A moving photographic plate* is used when a permanent record of the observed wave is required. The vibrations of the strip s, s, being in a horizontal plane, the photographic plate must be moved in a vertical plane; this is usually done by letting the plate fall down a slide, under the action of gravity. When it passes by the exposure aperture, the beam of light traces on it a curve. The time of the exposure is so short that the speed of the plate may be assumed as constant.

It is sometimes necessary to observe alternating-current phenomena which last a considerable time, such as observations on the paralleling of alternators, the running up to speed of motors, the surges which occur in switching on and off cables, etc. Photographic records are required here, considerably longer than those which can be obtained on a single plate. In these cases a camera is mounted in place of the vertical slide. A roll of cinematograph film, such as is used for moving pictures, is driven at a uniform speed, past the exposure aperture. Records over 100 feet long may be obtained at one time, giving the complete picture of the varying phenomenon.

(*b*) *Revolving or oscillating mirror.* With this method, a second mirror is interposed in the path of the beam of light, and is caused to

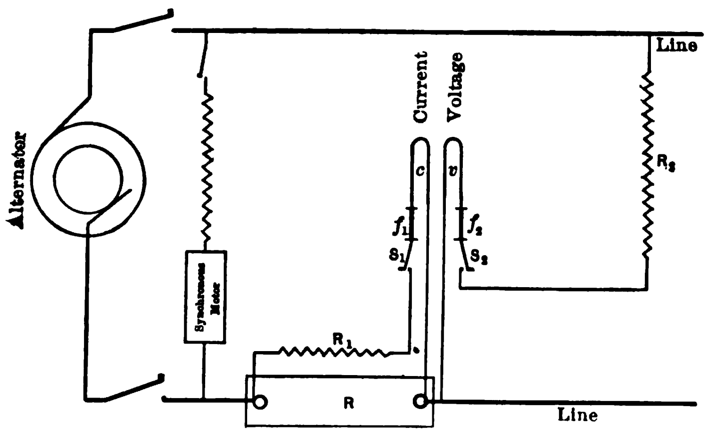


FIG. 482. Oscillograph connections for determining simultaneously a current wave and a voltage wave.

rotate, or to vibrate so as to impart to the beam of light a uniform motion at right angles to the vibrations due to the current. The spot of light then traces on a stationary screen a time-curve of variations of a voltage or a current, as the case may be (Fig. 479). If the variations are periodic, as in commercial alternating currents, the second mirror is synchronized, and the spot of light is caused to trace the wave form over and over again, so that it appears stationary to the eye, and may be easily observed. If it is desired to have it recorded, the beam of light is projected on a curved screen of ground glass (Fig. 481), where it may be traced by hand, or photographed.

653. The Duddell Double Oscillograph.—The outfit shown in Fig. 481 represents a double oscillograph which is a combination of two single oscillographs, placed side by side. The moving part of one is

connected across the terminals of the circuit and thus made to indicate the voltage wave; the other is connected as a milli-voltmeter across a non-inductive shunt in series with the circuit (Fig. 482).

The vibrating wire v, which traces the voltage wave, is connected across the line in series with a high resistance R_2; it is protected by a fuse f_2, and the switch S_2. The other vibrating wire c, which traces the current wave, is connected across a non-inductive shunt R; it is protected by the resistance R_1, fuse f_1 and switch S_1. The synchronous motor, shown in the sketch, is for driving the revolving or the vibrating mirror.

The oscillograph itself is shown in Fig. 481 to the left, its two small mirrors on the strips being illuminated by the projection lantern to the right. The light reflected from these mirrors falls on a vibrating mirror driven by a small synchronous motor, and is finally reflected on the curved screen; the vibrating mirror and the motor are shown under the tracing screen. Two curves are visible on the screen, the outfit being a double oscillograph.

The mirror is vibrated by means of a cam attached to the motor shaft. The cam is so arranged that the mirror moves uniformly for about 1½ complete periods, during which the wave form is observed it then returns rapidly to its starting point during the remaining ½ period. During the half period of return motion, the light is cut off from the oscillograph by means of a sector fixed to the motor.

Instead of a vibrating mirror, ordinary revolving mirrors may be used, provided with a sufficient number of faces, to give a suitable scale and a steady image.

When it is desired to produce waves to a larger scale, as for demonstration purposes, a large stationary mirror is substituted for the tracing screen, and the vibrating beam of light is thrown on the projection screen, or directly on the wall. Waves as high as 3 feet may be thus produced.

In taking oscillograph records, it is often desired to have the axis of abscissæ automatically marked on the record. This is done by providing a small *stationary* mirror in the oscillograph itself. This mirror gives a beam of light which is deflected by the revolving mirror along the axis of abscissæ, and traces this axis. Another way is to stretch a vertical wire before the falling photographic plate: The wire intersects the oscillating beam of light, and the axis of abscissæ is recognized on the record from the interruptions in the wave.

654. Students' Oscillograph. — The above-described oscillograph, used for accurate work, is rather delicate in handling and difficult to adjust. It is well for a beginner to start with a simpler and a more

robust instrument, for instance such as is shown in Fig. 483. Its moving system is based on the same principle as that in Fig. 480, but the wires are much heavier and no oil damping is provided. This oscillograph could not be expected to show high harmonics accurately; it may even introduce harmonics of its own; but some experience in handling this instrument is a valuable preparation for work with more accurate oscillographs.

The instrument shown in Fig. 483 is a double oscillograph; it has two oscillating loops which may be used either together or separately, for instance, one for amperes and the other for volts.

The light necessary for producing the spot on the screen is obtained from a projection lantern; the rays are concentrated on the mirrors by means of suitable lenses. The revolving mirror should have about 12 faces, and may be driven by a small fan motor. The speed of the mirror can be made a multiple of the frequency of the supply to be investigated. Then the curves appear stationary on the screen, and can be traced with sufficient accuracy. In addition to two spots of light, produced by the two small mirrors on the movable parts of the oscillograph, a third spot is thrown on the screen by a third stationary mirror. When the revolving mirror rotates, this spot traces a horizontal luminous line representing the axis of abscissæ.

FIG. 483. A student's oscillograph.

At the beginning of the experiment the three spots must be made to coincide on the screen, with the current off. This is done by varying the relative positions of the two oscillographs on the stand, and also the position of the third mirror, which traces the axis of abscissæ. When the current is put on, and the revolving mirrors stand still, the vertical lines produced on the screen by the alternating currents flowing through the oscillograph, must be perpendicular to the axis of abscissæ. After being thus adjusted the apparatus is ready for use.

The current should not be kept switched on for a long time, either in the moving part or the stationary field of the oscillograph. The

apparatus is not intended for continuous use, and can be damaged by being overheated. The same applies to the motor driving the revolving mirror. Open all the circuits as soon as a curve is taken and while connections are being changed for the next curve.

655. EXPERIMENT 31-B. — Determination of Alternating Current Wave-Form with an Oscillograph. — The work with an oscillograph (§§ 650 to 654) consists in taking some or all of the curves enumerated in connection with the point-to-point method (§ 649). The results must be worked out in the way indicated there. Similar curves should be taken by the two methods as, for instance, the wave form of the laboratory supply, which is practically invariable: the results can be compared and checked with each other.

WAVE ANALYSIS.

656. It is sometimes desired to express analytically an irregular wave, such as *PQR* (Fig. 484), taken by the point-to-point method

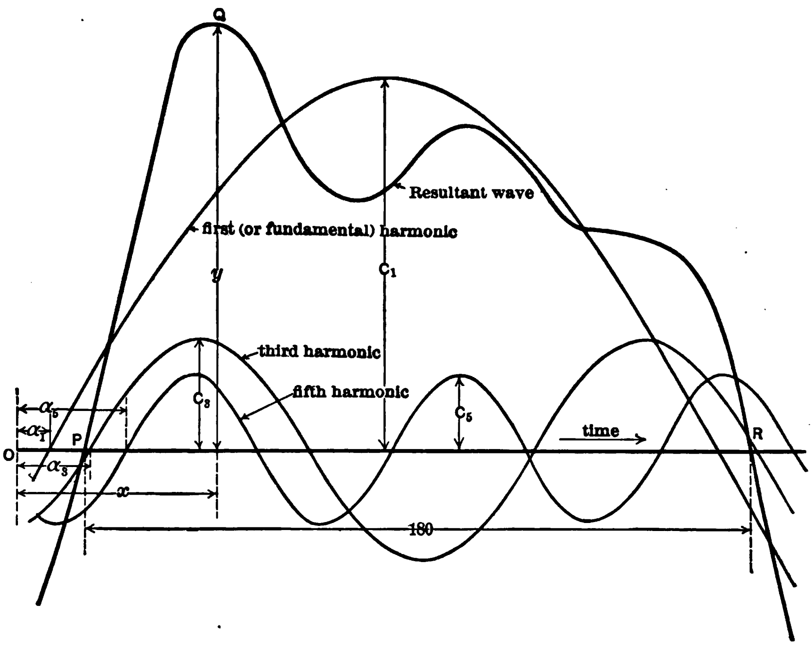


FIG. 484. A complex wave resolved into its harmonics. *O* is an arbitrary origin.

or by an oscillograph. *The equation of any periodic curve, no matter how irregular, may be represented by an infinite series of sine waves,*

one of which has the same frequency as the given curve, and the rest have frequencies which are multiples of it. Thus, the wave shown in Fig. 484 is a combination of three sine-waves, or, as they are called, *harmonics*; the fundamental wave C_1, the third harmonic C_3, and the fifth harmonic C_5. A rigid analytical proof of this law (Fourier's theorem) would be out of place here. It will be easily seen, however, without any proof, that by suitably selecting the frequency and the phase position of the higher harmonics, the shape of the fundamental sine wave may be distorted in almost any desired way.

When the two halves of the irregular wave, above and below the axis of abscissæ, are identical, no *even* harmonics, or harmonics having frequencies 2, 4, 6, etc., times higher than the given curve can be present. Such harmonics would increase the ordinates of one half of the fundamental wave, and reduce by the same amount the ordinates of the other half, making the wave unsymmetrical, which is contrary to the assumption of its being symmetrical. Practically all the waves of voltages and currents dealt with in electrical engineering are symmetrical waves, at least those produced by electromagnetic induction. They consist, therefore, of the fundamental and of the *odd* harmonics only.

657. General Equation of an Irregular Wave. — From the above considerations it follows that the general equation of the wave PQR shown in Fig. 484 is:

$$y = C_1 \operatorname{Sin} (x - \alpha_1) + C_3 \operatorname{Sin} 3 (x - \alpha_3) + C_5 \operatorname{Sin} 5 (x - \alpha_5) + \cdots$$

the meaning of all the symbols being shown in the sketch; O is an arbitrary origin. Opening the parentheses, we get

$$y = C_1 \operatorname{Cos} \alpha_1 \operatorname{Sin} x - C_1 \operatorname{Sin} \alpha_1 \operatorname{Cos} x + C_3 \operatorname{Cos} 3\alpha_3 \operatorname{Sin} 3x - C_3 \operatorname{Sin} 3\alpha_3 \operatorname{Cos} 3x + \cdots$$

or

$$y = A_1 \operatorname{Sin} x + B_1 \operatorname{Cos} x + A_3 \operatorname{Sin} 3x + B_3 \operatorname{Cos} 3x + \cdots \quad (1)$$

where for any harmonic, such as the nth,

$$\left.\begin{aligned} A_n &= + C_n \operatorname{Cos} n\alpha_n \\ B_n &= - C_n \operatorname{Sin} n\alpha_n \end{aligned}\right\} \quad \dots \quad (2)$$

The absolute values of the coefficients A_n and B_n are the amplitudes of the component waves of the nth harmonic (Fig. 486). The two components of the fifth harmonic are shown in this figure, the sine component and the cosine component. The first intersects the axis of abscissæ at the origin O; the second is displaced by $\frac{1}{2}\pi$.

Having found, by the method described below, the component harmonics, the magnitude and the phase position of the total harmonic (Fig. 484) of the same order are determined from the relations

$$\left.\begin{aligned} C_n &= \sqrt{A_n^2 + B_n^2}; \\ -\tan n\alpha_n &= B_n \div A_n. \end{aligned}\right\} \quad \dots \quad (3)$$

These formulæ are obtained from the expressions (2) for A_n and B_n. The values of C_n and α_n can also be measured graphically, as shown in Fig. 485, from the known values of A_n and B_n.

658. Expressions for Amplitudes of Higher Harmonics. — The amplitudes A_1, B_1, A_3, B_3, etc., of component harmonics are calculated on the basis of the following mathematical propositions:

(I) The integral

$$\int_0^\pi \text{Sin } mx \,.\, \text{Sin } nx \,.\, dx = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

except when $m = n$, in which case it becomes

$$\int_0^\pi \text{Sin}^2 nx \,.\, dx = \frac{\pi}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

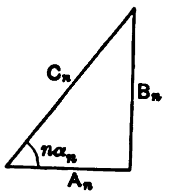


FIG. 485. The relation between a harmonic and its sine and cosine components.

(II) The same holds true when cosines are substituted for sines.

(III) The integral

$$\int_0^\pi \text{Sin } mx \,.\, \text{Cos } nx \,.\, dx = 0 \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

whether m is equal to n or not, provided, however, that both m and n are odd numbers, as is the case in the problem under consideration. A proof of the above propositions is given in § 660 below.

In order to eliminate all the coefficients in the expression (1), except A_n, both sides of the equation are multiplied by Sin nx, and integrated between the limits 0 and π. This gives

$$\int_0^\pi y \text{ Sin } nx \,.\, dx = 0 + 0 + \cdots + A_n \cdot \frac{\pi}{2} + 0 + 0 + \cdot \cdot \cdot \cdot$$

or

$$A_n = \frac{2}{\pi} \int_0^\pi y \text{ Sin } nx \,.\, dx \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

Similarly,

$$B_n = \frac{2}{\pi} \int_0^\pi y \text{ Cos } nx \,.\, dx \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

where $n = 1, 3, 5$, etc., according to the harmonic which is desired.

These integrals mean a summation of an infinite number of products, such as y Sin nx and y Cos nx. In applying these expressions in practice, one must be satisfied with a finite number of terms, and use an ordinary summation instead of integration.* We obtain, then,

* There are mechanical wave-analyzers on the market, by means of which the values of A and B are obtained by tracing the given wave with a point, as with a planimeter. See Orlich, *Aufnahme und Analyse von Wechselstromkurven* (Vieweg & Sohn); also W. S. Franklin, *Electric Waves*, p. 240.

$$A_n = \frac{2}{\pi}\sum_{o}^{q} y \operatorname{Sin} nx \cdot \frac{\pi}{q} = \frac{\sum_{o}^{q} y \operatorname{Sin} nx}{\frac{1}{2} q} \quad . \quad . \quad . \quad . \quad (9)$$

$$B_n = \frac{2}{\pi}\sum_{o}^{q} y \operatorname{Cos} nx \cdot \frac{\pi}{q} = \frac{\sum_{o}^{q} y \operatorname{Cos} nx}{\frac{1}{2} q} \quad . \quad . \quad . \quad . \quad (10)$$

where q is the number of parts into which 180° is subdivided (Fig. 486). The formulæ (9) and (10) are those used in practice for analyzing alternating-current waves, as is explained below.

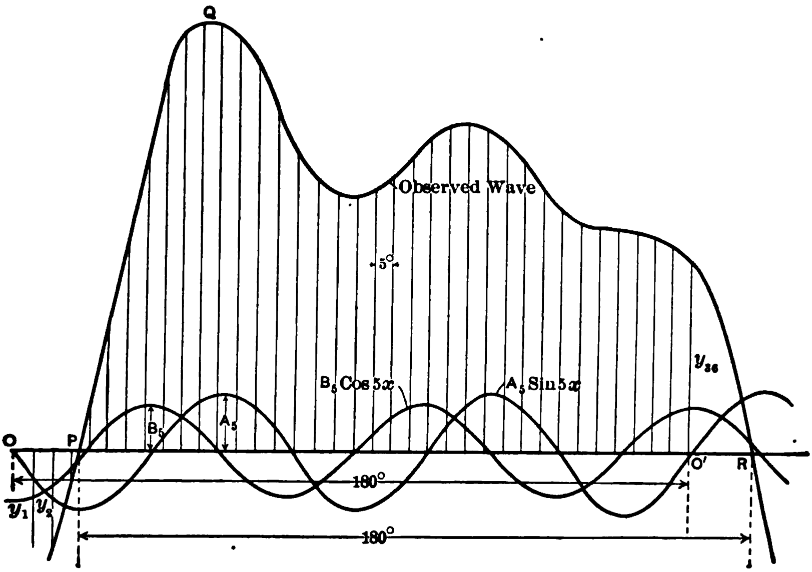


FIG. 486. The sine and cosine components of the fifth harmonic.

659. The Use of Analyzing Tables. — Suppose it is desired to separate the fifth harmonic of the current wave PQR shown in Fig. 486. Select an arbitrary origin O and divide the abscissa $OO' = 180°$ into a certain number of equal parts (the more the better). In the case shown, 180 degrees is divided into 36 parts, so that $q = 36$, and the distance between adjacent ordinates is 5 degrees. The angular distance of 5 degrees for the fundamental wave corresponds to an electric phase angle of 25 degrees for the fifth harmonic. Thus we have, according to equation (9),

$$A_5 = \frac{1}{\frac{1}{2} \cdot 36}\left\{ y_1 \operatorname{Sin} 25° + y_2 \operatorname{Sin} 50° + y_3 \operatorname{Sin} 75° + \ldots \right\} \quad . \quad . \quad (11)$$

$$B_5 = \frac{1}{\frac{1}{2} \cdot 36}\left\{ y_1 \operatorname{Cos} 25° + y_2 \operatorname{Cos} 50° + y_3 \operatorname{Cos} 75° + \ldots \right\} \quad . \quad . \quad (12)$$

where y_1, y_2, y_3, etc., are the measured ordinates of the curve PQR, beginning with the first division after the point O. The amplitudes A_5 and B_5 are calculated from these expressions, and then the total fifth harmonic is determined, in its amplitude C_n and phase position α_n, from eqs. (3); or else, the graphical solution, Fig. 485, can be used.*

The values of sines and cosines in the equations (11) and (12) are the same with all curves, provided the number of ordinates $q = 36$ is the same. Therefore, it is convenient to have the values of sines and cosines tabulated once for all, and merely multiply them with the ordinates y_1, y_2, y_3, etc., of a given curve. Such tables for the fundamental wave, the third, the fifth, and the seventh harmonics are given below. Similar tables may be prepared for any desired number of higher harmonics. Having tables of this kind, the calculation of the values of amplitudes A_n and B_n according to the equations (9) and (10) is much simplified. The measured ordinates y are entered in column 5 and multiplied with the sines in column 1. The results are written down in columns 2 and 3; the positive and the negative products are summed up separately. Then, according to equation (9) we have

$$A_n = \frac{1}{18}\left(\sum_{\text{pos.}}' - \sum_{\text{neg.}}'\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

In a similar way, by using the cosines in column 6, the following expression is obtained for the amplitude B_n:

$$B_n = \frac{1}{18}\left(\sum_{\text{pos.}}'' - \sum_{\text{neg.}}''\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

If a large number of curves are to be analyzed, it is convenient to have the tables on pp. 228–231 mimeographed or printed so as to avoid copying the values of sines and cosines for each curve.†

* The second equation (3) gives two values for the angle $n\alpha_n$, differing from each other by 180°. The question is decided by considering the signs of A_n and B_n. With reference to eqs. (2), and noting that C_n is essentially positive, we have the following four possibilities for the signs of A_n and B_n:

	$n\alpha_n$	A_n	B_n
between	0° and + 90°	pos.	neg.
"	+ 90° " + 180°	neg.	neg.
"	0° " − 90°	pos.	pos.
"	− 90° " − 180°	neg.	pos.

Let, for instance, the values of A_5 and B_5, as determined from eqs. (9) and (10), be as follows: $A_5 = -7.32$; $B_5 = +4.56$. From the table above we see that $5\,\alpha_5$ is between −90° and −180°; its tangent is equal to $4.56 \div 7.32 = .623$. The corresponding acute angle is 31° 55′, so that $5\,\alpha_5 = -148°\ 5'$, and $\alpha_5 = -29°\ 37'$.

† Extra copies of these tables may be had of the publishers, Messrs. John Wiley & Sons, New York City.

660. Proof of Formulæ (4), (5), and (6). — The expressions (4) (5) and (6) may be proved by direct integration, having previously substituted a sum or a difference of trigonometrical functions for their product. Thus, we have:

$$\operatorname{Cos}(m-n)x - \operatorname{Cos}(m+n)x = 2 \operatorname{Sin} mx \operatorname{Sin} nx,$$

so that the integral (4) is reduced to

$$\tfrac{1}{2}\int_0^\pi \operatorname{Cos}(m-n)\,x\,dx - \tfrac{1}{2}\int_0^\pi \operatorname{Cos}(m+n)\,x\,dx.$$

This, after integration, gives:

$$\tfrac{1}{2}\left[\frac{\operatorname{Sin}(m-n)\,x}{(m-n)}\right]_0^\pi - \tfrac{1}{2}\left[\frac{\operatorname{Sin}(m+n)\,x}{m+n}\right]_0^\pi$$

Each of these expressions is separately equal to zero, which proves equation (4).

When $m = n$, the above expression becomes indeterminate, so that equation (5) must be proved separately. We have

$$\operatorname{Sin}^2 nx = \frac{1 - \operatorname{Cos} 2\,nx}{2};$$

consequently

$$\int_0^\pi \operatorname{Sin}^2 nx.\, dx = \tfrac{1}{2}\Big[x\Big]_0^\pi - \tfrac{1}{2}\left[\frac{\operatorname{Sin} 2\,nx}{2\,n}\right]_0^\pi$$

The second term on the right side is equal to zero; the first term gives $\frac{1}{2}\pi$.

This proves equation (5).

Equation (6) is proved on the basis of the relation:

$$\operatorname{Sin}(m+n)\,x + \operatorname{Sin}(m-n)\,x = 2 \operatorname{Sin} mx \operatorname{Cos} nx.$$

After integration, we obtain:

$$\tfrac{1}{2}\left[\frac{\operatorname{Cos}(m+n)\,x}{m+n}\right]_0^\pi + \tfrac{1}{2}\left[\frac{\operatorname{Cos}(m-n)\,x}{m-n}\right]_0^\pi.$$

According to the conditions of the problem, both m and n are *odd* numbers (order numbers of harmonics): consequently $(m + n)$ and $(m - n)$ are *even* numbers. But cosine of an even multiple of π is always equal to 1. Therefore, each of the above terms is separately equal to zero. This proves equation (6).

APPENDIX.

The following tables of Sines and Cosines, are arranged for separating complex waves into harmonics — see expressions (13) and (14):

FUNDAMENTAL WAVE.

1	2	3	4	5	6	7	8
Sin x	Products $y \sin x$ (positive)	(negative)	No.	Measured Ordinates y	Cos x	Products $y \cos x$ (positive)	(negative)
.0872			1		.9962		
.1736			2		.9848		
.2588			3		.9659		
.3420			4		.9397		
.4226			5		.9063		
.5000			6		.8660		
.5736			7		.8192		
.6428			8		.7660		
.7071			9		.7071		
.7660			10		.6428		
.8192			11		.5736		
.8660			12		.5000		
.9063			13		.4226		
.9397			14		.3420		
.9659			15		.2588		
.9848			16		.1736		
.9962			17		.0872		
1.0000			18		.0000		
.9962			19		−.0872		
.9848			20		−.1736		
.9659			21		−.2588		
.9397			22		−.3420		
.9063			23		−.4226		
.8660			24		−.5000		
.8192			25		−.5736		
.7660			26		−.6428		
.7071			27		−.7071		
.6428			28		−.7660		
.5736			29		−.8192		
.5000			30		−.8660		
.4226			31		−.9063		
.3420			32		−.9397		
.2588			33		−.9659		
.1736			34		−.9848		
.0872			35		−.9962		
.0000			36		−1.0000		
	$\Sigma'_{pos}=$	$\Sigma'_{neg}=$				$\Sigma''_{pos}=$	$\Sigma''_{neg}=$

THIRD HARMONIC.

	2	3	4	5	6	7	8
Sin 3 x	Products y sin 3 x (positive)	(negative)	No.	Measured Ordinates y	Cos 3 x	Products y cos 3 x (positive)	(negative)
.2588			1		.9659		
.5000			2		.8660		
.7071			3		.7071		
.8660			4		.5000		
.9659			5		.2588		
1.0000			6		.0000		
.9659			7		−.2588		
.8660			8		−.5000		
.7071			9		−.7071		
.5000			10		−.8660		
.2588			11		−.9659		
.0000			12		−1.0000		
−.2588			13		−.9659		
−.5000			14		−.8660		
−.7071			15		−.7071		
−.8660			16		−.5000		
−.9659			17		−.2588		
−1.0000			18		.0000		
−.9659			19		.2588		
−.8660			20		.5000		
−.7071			21		.7071		
−.5000			22		.8660		
−.2588			23		.9659		
.0000			24		1.0000		
.2588			25		.9659		
.5000			26		.8660		
.7071			27		.7071		
.8660			28		.5000		
.9659			29		.2588		
1.0000			30		.0000		
.9659			31		−.2588		
.8660			32		−.5000		
.7071			33		−.7071		
.5000			34		−.8660		
.2588			35		−.9659		
.0000			36		−1.0000		
	$\Sigma'_{pos}=$	$\Sigma'_{neg}=$				$\Sigma''_{pos}=$	$\Sigma''_{neg}=$

FIFTH HARMONIC.

1	2	3	4	5	6	7	8
Sin 5 x	Products (positive)	y sin 5 x (negative)	No.	Measured Ordinates y	Cos 5 x	Products (positive)	y cos 5 x (negative)
.4226			1		.9063		
.7660			2		.6428		
.9659			3		.2588		
.9848			4		−.1736		
.8192			5		−.5736		
.5000			6		−.8660		
.0872			7		−.9962		
−.3420			8		−.9397		
−.7071			9		−.7071		
−.9397			10		−.3420		
−.9962			11		.0872		
−.8660			12		.5000		
−.5736			13		.8192		
−.1736			14		.9848		
.2588			15		.9659		
.6428			16		.7660		
.9063			17		.4226		
1.0000			18		.0000		
.9063			19		−.4226		
.6428			20		−.7660		
.2588			21		−.9659		
−.1736			22		−.9848		
−.5736			23		−.8192		
−.8660			24		−.5000		
−.9962			25		−.0872		
−.9397			26		.3420		
−.7071			27		.7071		
−.3420			28		.9397		
.0872			29		.9962		
.5000			30		.8660		
.8192			31		.5736		
.9848			32		.1736		
.9659			33		−.2588		
.7660			34		−.6428		
.4226			35		−.9063		
.0000			36		−1.0000		
	$\Sigma'_{pos} =$	$\Sigma'_{neg} =$				$\Sigma''_{pos} =$	$\Sigma''_{neg} =$

SEVENTH HARMONIC.

1	2	3	4	5	6	7	8
Sin 7 x	Products y sin 7 x (positive)	(negative)	No.	Measured Ordinates y	Cos 7 x	Products y cos 7 x (positive)	(negative)
.5736			1		.8192		
.9397			2		.3420		
.9659			3		−.2588		
.6428			4		−.7660		
.0872			5		−.9962		
−.5000			6		−.8660		
−.9063			7		−.4226		
−.9848			8		.1736		
−.7071			9		.7071		
−.1736			10		.9848		
.4226			11		.9063		
.8660			12		.5000		
.9962			13		−.0872		
.7660			14		−.6428		
.2588			15		−.9659		
−.3420			16		−.9397		
−.8192			17		−.5736		
−1.0000			18		.0000		
−.8192			19		.5736		
−.3420			20		.9397		
.2588			21		.9659		
.7660			22		.6428		
.9962			23		.0872		
.8660			24		−.5000		
.4226			25		−.9063		
−.1736			26		−.9848		
−.7071			27		−.7071		
−.9848			28		−.1736		
−.9063			29		.4226		
−.5000			30		.8660		
.0872			31		.9962		
.6428			32		.7660		
.9659			33		.2588		
.9397			34		−.3420		
.5736			35		−.8192		
.0000			36		−1.0000		
	$\Sigma'_{pos}=$	$\Sigma'_{neg}=$				$\Sigma''_{pos}=$	$\Sigma''_{neg}=$

CHAPTER XXXII.

SWITCHBOARDS.

661. THE switchboard is an essential part of every electric plant, its object being to group together at some convenient and accessible place the necessary devices for controlling and distributing the current to the various circuits for measuring the power received or delivered, and for supporting safety devices which protect the machines and the lines.

The following laboratory exercises are intended to familiarize the student with the construction and operation of standard switchboards; also with the types and functions of the principal switchboard devices and their electrical connections.

In beginning the study of the subject, the student should first operate a switchboard in order to learn the purpose of its various devices. The next step is to study actual electrical connections and to learn to trace them out on a given switchboard. The more advanced student should himself design the connections and connect up a switchboard according to his design. This work is provided for in the exercises in assembling switchboards.

I. DIRECT-CURRENT SWITCHBOARDS.

662. Switchboards for One Direct-Current Generator. — A simple direct-current switchboard, suitable for a small isolated plant, is shown in Fig. 487. The connections are practically the same as in the diagram Fig. 193, except that no field ammeter is used as a rule; the field rheostat is adjusted so as to obtain the required terminal voltage. The switchboard itself consists of panels of marble or slate, supported by frames of angle iron or gas-pipe. The large switch in the center connects the switchboard to the generator. The handle of the field rheostat is seen above it, the rheostat itself being mounted on the back of the switchboard. The ammeter and the voltmeter are mounted near the top.

Lamps are sometimes provided for illuminating the instrument scales: the lamps are connected directly to the main cable coming from the machine, so as to light up even when the main switch is open. Two ground-detector lamps are visible in the upper corners of the panel; for their operation see § 479. Four smaller switches shown to the left and to the right are feeder switches controlling four outgoing circuits.

Each switch circuit is protected by fuses, visible under the switches. Automatic circuit-breakers are coming more and more into use instead of switches and fuses.

The main switch is connected to two horizontal copper bars, commonly called bus-bars, so that the generator power is delivered to the bus-bars. The feeder switches are also connected to the bus-bars, and in this way the energy taken from the generator is delivered to various feeder circuits.

663. EXPERIMENT 32-A.—Tracing out Connections on a Direct-Current Generator Panel.—The purpose of the experiment is to illustrate the connections and the operation of a simple direct-current generator switchboard. The principal features of construction and connections are given in the preceding article; some small variations may be met with in switchboards of different makes.

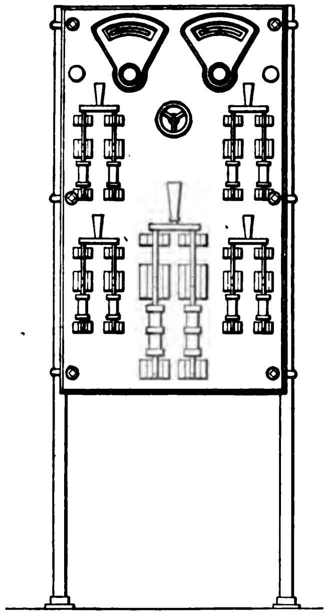


FIG. 487. An isolated-plant direct-current switchboard, for one generator and four outgoing feeders.

In tracing out the connections, first estimate, as closely as possible, the destination of the various parts. Then make a rough sketch of the arrangement of the apparatus on the front of the switchboard and of the principal parts on the back, first without wiring. Finally put on the sketches all the electrical connections, and see if they are correct.

If some connections are inaccessible, or invisible, trace them out by putting current on, — for instance, through a lamp connected to an ordinary lighting supply. A galvanoscope and a dry cell, or a magneto and a bell, may also be used for tracing connections.

Having traced out all the connections, verify your understanding of their functions by actually operating the switchboard in the way in which it is supposed to be used during regular service. Make a note of the sizes and ranges of measuring instruments, switches, fuses, etc.

Report. Draw a diagram of actual connections; make a sketch of the assembly, as in Fig. 487. Give the ranges of the instruments and the size of other devices, — for instance, 75-ampere 250-volt switches,

50-ampere fuses, etc. Give instructions for operating the switchboard when starting the machine and when shutting down the plant.

664. EXPERIMENT 32-B. — Assembling a Direct-Current Generator Panel. — The purpose of the exercise is to gain experience in designing and assembling switchboards and handling switchboard apparatus. The principal features of construction, and connections used in small direct-current plants, are described in §§ 662 and 663. Small changes may be necessary with special requirements, or with the equipment at hand.

A special wooden panel should be provided with universal clamps for mounting the equipment in any desired place. The students are expected to design the connections, to mount and to connect up instruments, switches, etc. The finished switchboard should be connected to a generator and tried in operation.

In doing this work, particular attention should be paid to placing all the devices systematically, so that they occupy a minimum space. All similar devices should be placed if possible in one horizontal row: the measuring instruments must occupy such a height as to be conveniently read by the switchboard attendant; the circuit-breakers must be placed in the top row, so as not to hit the attendant when opening the circuit. The rheostat handles are placed so that the attendant can operate them, at the same time watching the instruments; the switches are placed where the space is available, usually in the lower row. The integrating wattmeters are read infrequently, and can, therefore, be mounted at any place, even on the wall outside the switchboard if no other space is available.

All the wiring must be placed on the rear of the switchboard; the work must be done neatly, must all be visible, and be securely fastened in the right position. No slanted wires are allowed, as a rule; the wires must run either horizontal or vertical with a sharp bend.

Report. Draw the diagram of connections used, and a sketch showing the actual arrangement of apparatus on the panel. Figure out the sizes and the ranges of the apparatus to be used for a plant of a certain given capacity. The rules for doing this are given in § 668 below. Include brief instructions for operating the switchboard.

665. Direct-Current Switchboards for Two or More Generators. — Switchboard connections for two compound-wound generators are shown in Fig. 488. The two outside panels are generator panels. The middle panel is for the outgoing feeders. The left-hand panel is shown with all the connections; the right-hand panel is left unconnected.

The main bus-bars extend throughout the whole length of the switchboard. The negative terminals of the machines are connected directly to the negative bus-bar, through the main switches. The positive cables are connected to the corresponding bus-bar through the circuit-

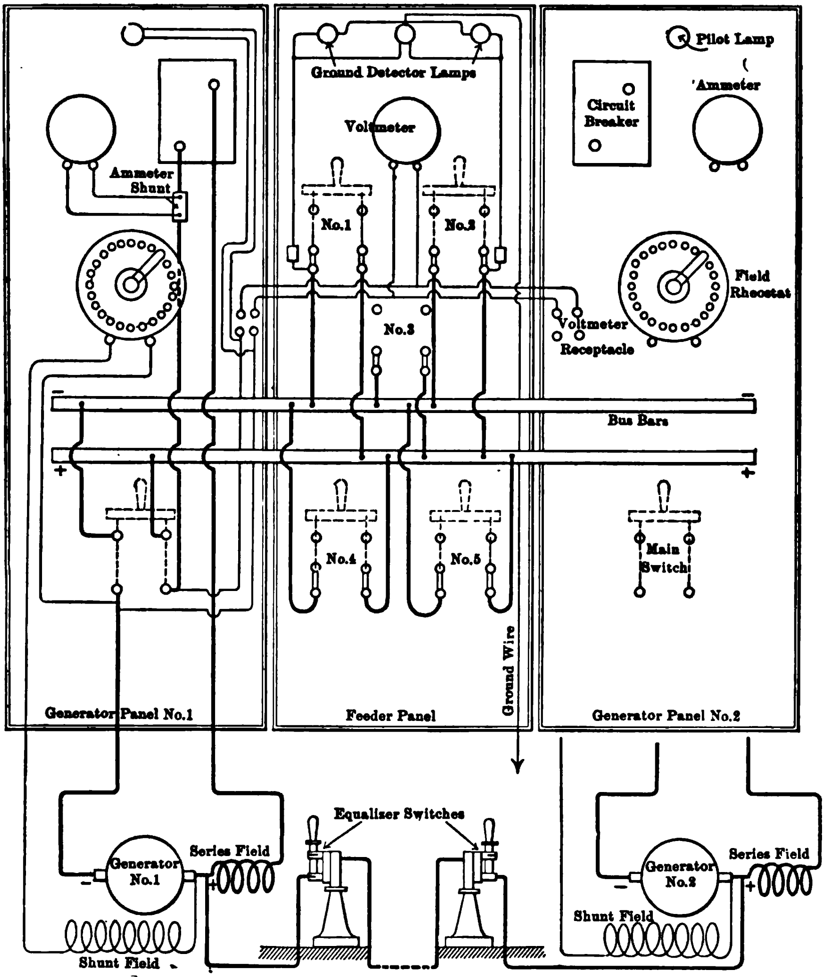


FIG. 488. Switchboard connections for two compound-wound generators and five feeders.

breakers and the ammeters. One terminal of each field circuit is taken to the switchboard, in order to have it connected to the field rheostat.

One voltmeter is used for both machines. It may be connected to either machine by means of a receptacle and a plug; the plug is shown

separately in Fig. 489. Each generator panel is provided with a lamp which serves for illuminating the ammeter scale and also as a pilot lamp. The feeder panel has three lamps on top. The middle one is connected across the bus-bars and illuminates the voltmeter scale. The two outside ones are ground-detector lamps; they are connected as shown in Fig. 378. Five feeder switches are shown on the middle panel, each circuit being protected by fuses. Circuit breakers, taking the place of both fuses and switches, are much used at present.

The equalizing connection shown between the positive brushes of the machines is used with compound-wound generators only, its purpose being to make the two machines divide the load equally. The theory of the equalizer is given in §§ 237 and 238. It is explained there that with large machines two single-pole switches should be used, instead of one double-pole main switch, in order to avoid an inrush of current when the machine is switched in. In small plants where this circumstance is of no particular importance, the equalizer switch and the main switch are combined into one three-pole switch.

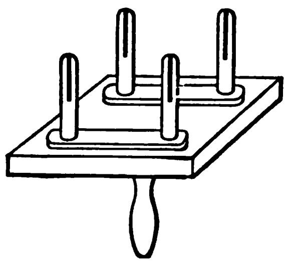


FIG. 489. Voltmeter plug.

The connections shown in Fig. 488 may be extended to any number of generators and of feeder panels. The equalizer cable runs through the station alongside the generators, and each machine is connected to it by its equalizer switch, usually mounted on a pedestal.

Watt-hour meters are frequently mounted on the switchboards, the connections being as shown in Fig. 87.

Tirrill regulators are now coming into use for automatically maintaining constant voltage. Their construction and connections are described in § 231. The regulator is mounted either on the panel itself if room is available, or on a bracket on one side of the switchboard.

666. EXPERIMENT 32-C. — Tracing out Connections on Large Direct-Current Switchboards. — The experiment is performed on a switchboard such as is shown in the diagram of Fig. 488, in the same way as experiment 32-A (§ 663).

667. EXPERIMENT 32-D.— Assembling Direct-Current Switchboards. — The experiment is performed in the same way as experiment 32-B (§ 664). For the experiment, two generators and all the necessary instruments and auxiliary apparatus should be available.

668. Determination of the Sizes of Switchboard Apparatus. — In the reports on some of the above-described experiments it is required

to determine the sizes of switchboard apparatus for a given capacity of the plant. A few explanations may make the calculations easier.

(*a*) *Switches.* Suppose, for instance, the size of the plant to be 500 kw. and the pressure 250 volts. If there are two machines, each machine has a capacity of 250 kw., or must deliver at full load 1000 amperes. This is the maximum current which the main switches have to carry continuously. Some margin should be allowed for possible short overloads, say 50 per cent, but the exact percentage of this allowance depends entirely upon the character of the plant and the duty for which it is intended. It seems that the above figure, 50 per cent, fairly well represents the average conditions. Thus, the switches must be of a 1000-ampere 250-volt type; they must be capable of safely opening the circuit when carrying a load of 1500 amperes (in case of an emergency).

(*b*) The range of *main ammeters* is calculated in the same way as that of the switches.

(*c*) *Bus-bars.* Tables will be found in electrical pocket-books giving the sizes of copper bar for various current-carrying capacity.

(*d*) *Field rheostats.* Their range is usually given in ohms, and in amperes carrying capacity, with all rheostat " in " and " out." According to the size of the machines, *from* 2 *to* 5 *per cent of the main current is consumed in field excitation;* this gives the amperage of the rheostat. For instance, in the above example the maximum field current of each machine may be assumed to be about 35 amperes. Therefore, the total resistance of the field winding, when rheostat is all " out," is $250 \div 35 =$ about 7 ohms. It is customary to give the field rheostat such a resistance that the field current could be reduced to one half its full value. Thus, in our case, the resistance of the field rheostat must be also about 7 ohms, and its current-carrying parts must be so dimensioned that it can stand continually and without excessive heating 35 amperes with the resistance all " out," and about 18 amperes with the resistance all " in." This is called in practice a " taper two to one " rheostat.

(*e*) *Overload circuit-breakers and fuses.* They should open the circuit when the current exceeds, by a certain percentage (say 50%), the full rated capacity of a machine; their size is figured out in the same way as that of the switches and ammeters.

(*f*) *Voltmeters.* Usually 110-volt plants are supplied with 150-volt instruments; 250-volt plants with 300-volt instruments, etc. This gives in each case a sufficient margin, should the voltage for some reason rise above normal.

(*g*) *Watt-hour meters.* These are rated in volts and amperes; for instance, in the above-quoted example a meter must be used whose

series windings can stand about 3000 amperes as a maximum on overloads (2000 amperes continual capacity), and the potential winding designed for 250 volts.

(*h*). *Cables to generators* are figured out from tables giving their safe carrying capacity.

Designing switchboards gives an opportunity for becoming acquainted with the catalogs of leading manufacturers of switchboard supplies, also with the commercial types, notations, prices, etc. Not every size of switch or of an instrument can be found in the catalogs, and the student should use his judgment in selecting the nearest suitable type. Give, in the report, the calculated sizes and those selected from the catalogs, using manufacturer's notation.

669. Miscellaneous Direct-Current Switchboards. — Generator switchboards described in the preceding articles do not exhaust all the types of direct-current switchboards used in practice, but they are the most important, and offer the greatest variety of equipment. With a clear understanding of generator switchboards, the construction and operation of other types of switchboards will be easily understood from the requirements of service. Among such switchboards are those used in connection with motors, rotary converters, arc lamps, storage batteries, boosters, etc.

2. ALTERNATING-CURRENT SWITCHBOARDS.

670. Switchboards for One Alternator. — The connections for a simple alternating-current switchboard are shown in Fig. 490; such switchboards are used in small single-phase plants distributing current mainly for lighting. In general appearance the switchboard is similar to those shown in Figs. 487 and 491.

The generator is connected to the main bus-bars through the main switch, fuses and the ammeter. The ammeter is shown connected into the circuit through a series transformer (see Fig. 44). Series transformers are used for two reasons: (1) They permit manufacturing all ammeters of the same actual range (usually about 5 amp.), the range being multiplied in any desired ratio through a series transformer; (2) The ammeter is insulated by the transformer from the line, which may have a voltage of 2200 volts or more; this adds to the safety of the operator.

Two-phase and three-phase switchboards have similar connections, except that ammeters are usually provided in all phases, and three or four bus-bars are used, Figs. 491 and 492.

The voltmeter is shown connected across the main bus-bars; it could also be connected across the main switch, as in Fig. 488. The

voltmeter is provided with a potential transformer for the same reasons for which the series transformer is used with the ammeter. A ground detector is used instead of ground-indicating lamps, because with voltages of 1000 volts and above, too many lamps in series would be required. The instrument is essentially an electrostatic voltmeter: the two line wires are connected to two stationary elements, the movable element is connected to the ground. When the insulation of the line is perfect, equal static charges are induced on both ends of the moving element; when one of the wires is grounded, the movable ele-

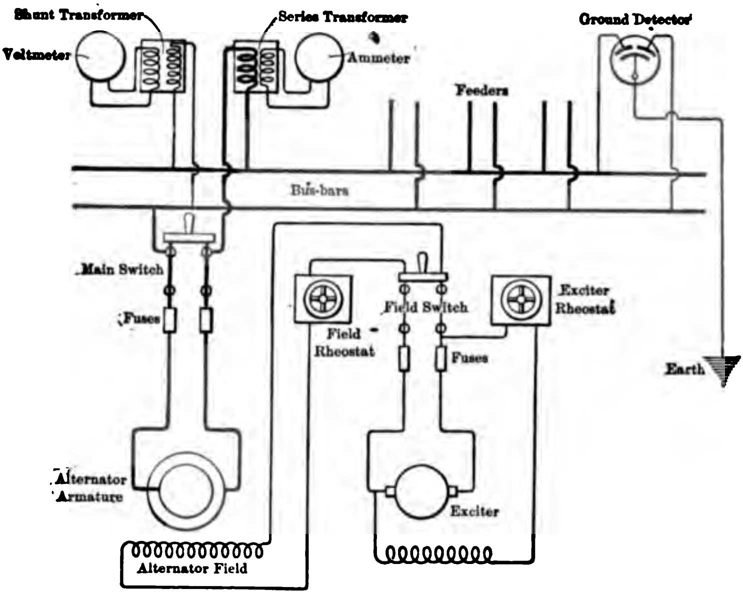


FIG. 490. Switchboard connections for one single-phase alternator.

ment is attracted more strongly to the side which is not grounded; this is shown by a pointer on the scale. The scale is calibrated in ohms or in any arbitrary units (see also § 478).

Direct current for exciting the field of the alternator is supplied by a small direct-current machine, so-called *exciter*. The exciter may be either direct connected to the alternator, belted to it, or driven by its own prime-mover. In large installations, exciters are usually driven by separate engines or electric motors.

The main circuit of the exciter and one of the terminals of its field winding are taken to the switchboard and connected to the regulating rheostats. The alternating voltage is adjusted by regulating either

rheostat. It is more economical to have as little resistance as possible in the rheostat to the left (" Field Rheostat "), voltage adjustment being obtained by suitably regulating the exciter field. Experience shows, however, that enough range cannot be obtained in this way for all conditions of load, and it is necessary to use also the rheostat to the left. The handles of the two rheostats are sometimes arranged concentrically, one within the other, as in Fig. 491, for economy in space.

671. EXPERIMENT 32-E. — Tracing out Connections on an Alternator Panel. — The principal features of construction and connections are described in the preceding article. For the conduct of the experiment and the requirements of the report see § 663.

672. EXPERIMENT 32-F. — Assembling an Alternator Panel.— The principal features of construction and connections are described in § 670. For the conduct of the experiment and the requirements of the report see § 664.

673. Switchboards for Two or More Alternators. — Two or more alternators may supply power in parallel to the same bus-bars, provided the machines are *in synchronism* with each other. This means that they must have the same frequency, and that the induced voltages must reach their maxima at the same time. Unless this condition is fulfilled, one generator will send part of its current into the other (see § 327). Thus when two or more alternators are connected to the same bus-bars, special synchronizing connections must be provided in addition to the equipment shown in Fig. 490. These connections are described in the next article.

A medium-size switchboard for two three-phase alternators is shown in Fig. 491. The middle and the left-hand panels are generator panels; the right-hand panel contains ammeters and switches for two feeders. Each generator panel is provided with three ammeters (one for each phase), a field rheostat, a three-pole main switch, and plug switches in the field circuit. The synchronizing and the line voltmeters are mounted on the bracket to the left. The synchronizing lamps and the receptacles for voltmeter and synchronizing plugs are clearly seen in the sketch.

Alternators do not always run satisfactorily in parallel, particularly when driven by gas engines. It is sometimes preferred, at least in small installations, to run the machines separately, distributing the load between them as well as possible. Two sets of bus-bars are therefore provided, one alternator being connected to the upper bars, the other to the lower ones. The outgoing feeders are connected to

double-throw switches, and may be supplied with current from either machine.

674. Synchronizing Connections. — The connections for synchronizing several three-phase alternators are shown in Fig. 492. Before the main switch of a machine is closed, the machine is brought into synchronism with the other machines already connected to the bus-bars. The connections are such that the same synchronizing lamps are

FIG. 491. A switchboard for two three-phase alternators and two outgoing lines.

used with all the machines. Separate synchronizing bus-bars are provided, the lamps being connected between these and the main bus-bars. Each incoming machine may be connected to the synchronizing bus-bars through the synchronizing receptacle, by a suit-

able plug being inserted into the receptacle. After synchronism has been obtained the main switch of the machine is closed. The plug may be left in the receptacle, until it is needed for synchronizing another alternator.

A synchroscope (see § 329) is shown in addition to the synchronizing lamps. Both are usually provided on large switchboards, and either or both may be used as desired. In high-voltage installations the lamps and the synchroscope are connected to the bus-bars through potential transformers.

675. Voltmeter Connections. — One voltmeter is ordinarily used for indicating the voltage of any number of alternators; the connections are shown in the lower part of Fig. 492. The voltmeter is connected to so-called voltmeter bus-bars, and each machine is provided with a voltmeter receptacle, by means of which the voltmeter may be

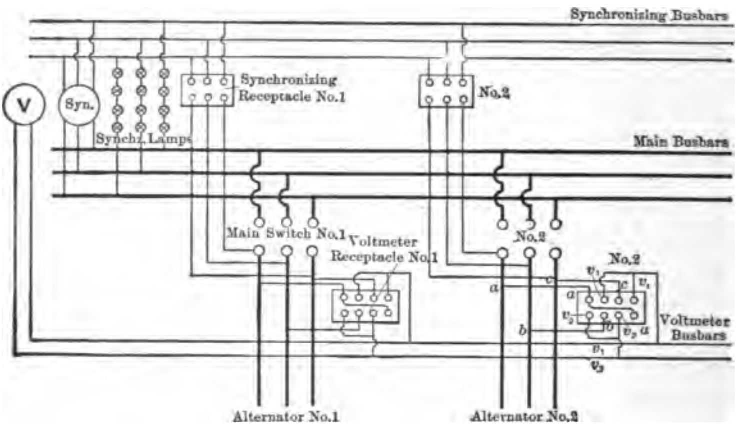


FIG. 492. Synchronizing and voltmeter connections for three-phase alternators.

made to indicate the pressure in either phase of any machine. The corresponding plug is shown in Fig. 489. The connections to alternator No. 2 are lettered and can be easily followed. When the voltmeter plug is inserted into the four holes to the left, *a* is connected to v_1, and *b* is connected to v_2, so that the voltmeter reads the voltage in the phase *a-b*. When the plug is in the four middle holes the voltmeter shows the voltage *b-c*; with the plug in the four holes to the right, the pressure in *a-b* is indicated.

A second voltmeter is connected permanently to the main bus-bars. This is necessary for watching the line voltage while one of the machines is being synchronized and the first voltmeter is disconnected from the line. Both voltmeters are sometimes mounted on a swing-

ing arm, as shown in Fig. 491; the voltmeter receptacles are also shown on the left and the middle panels.

676. Special Instruments. — *Watt-hour meters* are frequently mounted on switchboards. The connections are shown in Fig. 92 for single-phase wattmeters, and in Fig. 98 for three-phase wattmeters. As these instruments are read at infrequent intervals only, they may be mounted in any available space.

Indicating wattmeters are generally used on large switchboards, mostly for measuring the power output of each individual generator. The connections are the same as with watt-hour meters.

Special instruments are sometimes used on switchboards to enable the attendant to follow more closely the operation of the machines; as such instruments, *power-factor meters* (§ 82) and *frequency meters* (§ 555) are in quite general use. *Recording instruments* (§ 50) are also becoming more and more popular with power-station engineers.

Tirrill regulators are now coming rapidly into use for automatically maintaining a constant line voltage. Their construction and connections are described in § 325. The regulator is mounted either on the panel itself, if space is available, or on a bracket at one side of the switchboard.

677. EXPERIMENT 32-G. — Tracing out Connections on Large Alternating-Current Switchboards. — For a description of switchboards see §§ 673 to 676. The directions for the conduct of the experiment are the same as § 678.

678. EXPERIMENT 32-H. — Assembling Alternating-Current Switchboards. — For a description of switchboards see §§ 673 to 676. The directions for the conduct of the experiment are similar to those in § 664.

679. Remote-Control Switchboards. — With alternators of several thousand kilowatts capacity, the switches become too heavy to be operated by hand. Aside from this, it is not safe to operate them by hand because of the extremely high voltages commonly used in large power houses.

For these two reasons, oil switches — controlling generator and feeder circuits — are usually placed in a safe and convenient place apart from the switchboard. They are opened and closed by solenoids or small motors connected to an auxiliary low-voltage circuit. The operator has the control of the auxiliary circuit on the main switchboard, and opens and closes the main switches by operating small auxiliary switches. Tell-tale indicators or lamps are provided, so that the operator may see whether a certain switch is open or closed.

CHAPTER XXXIII.

ELECTRIC CONTROLLERS.

680. An electric controller, in the specific sense of the word, is a device for starting, regulating speed of, and reversing electric motors. Simpler types of direct-current motor starters and regulators are described in Chapter XIX; starting devices for induction motors are explained in § 335. This chapter contains a description of more complicated, or special, starting, regulating, and reversing devices. Railway controllers are treated in the next chapter.

To show a practical need for such devices, reference is made to Fig. 212, which shows a complete diagram of connections for operating a shunt-wound direct-current motor. The motor must be provided with a variable resistance for starting, and also with a field rheostat, if speed adjustment is required; besides, there must be a switch in the main circuit. If it is necessary to operate the motor in both directions, a double-throw switch must be added, so connected that it reverses the current either in the armature alone or in the field only. Sometimes motors are operated on a three-wire system, in which case the connections become still more complicated, especially if the motor must be reversible.

But the use of three or more separate switches and regulating devices cannot be tolerated in practice, this being too awkward and complicated for the operator. It is particularly objectionable in cases where motors are started and reversed many times a day, or are intrusted to persons incompetent in electrical matters, for instance to machine tool operators. All, or practically all, the necessary switches and rheostats must be either combined into one device, or must be mutually interlocked, so as to make an operation in a wrong order impossible.

A study of such improved starting and regulating devices is the subject of this chapter. The connections illustrated refer to direct-current motors only, because, so far, direct-current motors have been principally used for variable-speed work. The student will have no difficulty in applying the principles here explained to alternating-current motors. With the increasing uses of electric motors in all kinds of industries, and particularly with the steadily increasing sizes

of individual motors, the questions of speed control, quick reversal, etc., become more and more important. It is necessary, therefore, for the student to become familiar at least with the fundamental principles underlying the design and the operation of electric controllers.

681. Drum-type Controller. — The most common form of controller is the *drum-type controller*, quite widely used with individually driven machine-tools, such as lathes and milling machines. In its construction, such a controller is similar to an ordinary street-car controller, shown in Fig. 502. The wires coming from the line, from the motor, and from the starting and regulating resistances, are all connected to stationary controller " fingers," and these are brought into the necessary combinations by the connecting copper pieces, mounted on the revolving drum (Fig. 51). The drum is operated by a handle, and in each position of the handle various fingers are connected in a different way, so as to vary the speed of the motor, the direction of rotation, etc.

An ordinary machine-tool controller has, in the most general case, to perform the following three duties: (*a*) to start the motor, (*b*) to reverse the motor, and (*c*) to vary the speed. However complicated the connections inside the controller may be, the machinist does not need to know about them: all he has to do is to turn the handle one way or the other; the controller does the rest.

Motors used for driving machine-tools are mostly shunt-wound (in few cases compound-wound). The motor is started with some additional resistance in the armature circuit, in order to limit the rush of current; this resistance is gradually cut out as the motor gains speed. Speed is regulated either by varying the field current by means of a resistance in the field circuit, or by varying the pressure at the armature terminals (multi-voltage system). When an exceptionally wide range of speed control is required, both methods are used in combination. To reverse the motor, the armature leads are interchanged, the direction of the current in the field circuit remaining the same at all times.

682. Elementary Controller Connections. — Two examples of actual connections in drum-type machine-tool controllers are shown in Figs. 497 and 498. Before attempting to study their connections, it is advisable to make clear to oneself more elementary connections, shown in Figs. 493 to 496. The connections shown in Figs. 497 and 498 are but combinations of these.

In all these diagrams the controller drum is shown developed on a plane; different positions of the fingers *a*, *b*, *c*, etc., on the copper strips *x*, *y*, *z*, are indicated by dotted vertical lines. Fig. 493 gives the starting connections only. On the first notch the current from one terminal

of the line passes through the finger *a*, the strips z_1, x_4, x_3, x_2, and x_1 to the finger *e*, thence through the whole starting resistance to the armature of the motor and out to the other terminal of the line. On the

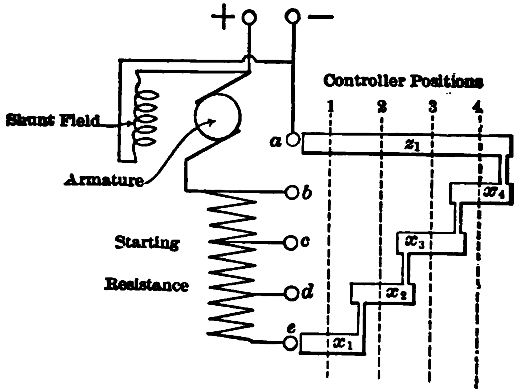


FIG. 493. Starting connections.

second notch the finger *d* touches the strip x_2, and part of the starting resistance, that between *d* and *e*, is cut out. On the third notch still more resistance is cut out, and finally on the fourth notch the current

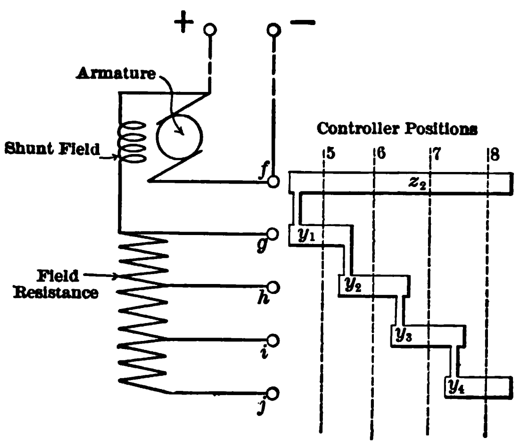


FIG. 494. Field-control connections.

flows through *a*, *z*, x_4 and *b* direct to the armature, without any starting resistance in series: this is the running position of the drum.

Fig. 494 represents controller connections for speed control, by means of a variable resistance in the field circuit; for the sake of clearness the starting connections are omitted. On the fifth notch the field is excited

directly across the line, without any resistance in series with it. This gives the strongest field, and therefore the lowest speed. On the sixth notch the resistance between the fingers g and h is inserted into the circuit, on the next notch that between g and i, etc., until on the last notch the whole field resistance is put into the circuit, and the motor runs at its highest speed.

Connections for reversing the motor are shown in Fig. 495. When the drum is in the "Forward" position, the current from the positive terminal flows through n, u_1, u_2, and m to the armature terminal A_1, and thence returns to the line through the terminal A_2. When the controller handle is in the "Reverse" position, the current passes through n, v_1, v_3, and l to the armature terminal A_2, thus flowing through the armature in the opposite direction. Therefore, the motor now runs in the opposite direction, the field connections not being reversed.

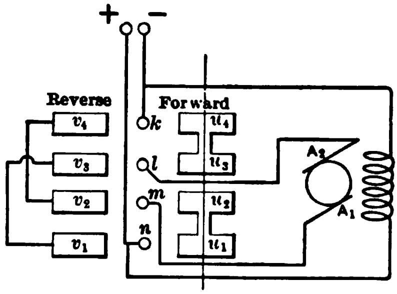


FIG. 495. Connections for reversing (starting positions omitted).

Controller connections for operating a motor on a three-wire system (§ 240) are shown in Fig. 496. In the position marked "Half-speed" the armature is connected between the positive and the neutral (±) wires; at full speed it is connected between the positive and the negative terminals.

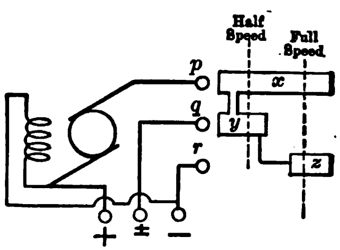


FIG. 496. Three-wire connections (starting positions omitted).

683. Examples of Actual Connections. — With a clear understanding of the above simple diagrams, the following out of the connections in Figs. 497 and 498 will hardly offer any difficulties. Fig. 497 represents the connections in a single-voltage reversible controller. The motor shown is compound-wound, but the series field has nothing to do with the operation of the controller, which can just as well be used with a shunt-wound motor. The controller has two starting positions, 1 and 2, in which the armature resistance is gradually cut out of the circuit; the other positions are for field control.

The line, the armature leads, and one of the terminals of the field are connected to the fingers corresponding to the long strips, and are in the

circuit for all positions. The "Forward" strips and the "Reverse" strips are so connected, that the current flows through the armature in opposite directions. The shorter upper strips are for cutting out starting resistance in steps. The lower diagonal strips serve for gradually introducing resistance into the field. Fewer steps are provided on the "Reverse," because it is not supposed to be used in regular operation.

The controller shown in Fig. 498 is designed for a three-wire system. No starting-notches are provided; the starting resistance is automatically cut out in one step by a spring-actuated contact *c*, which is released

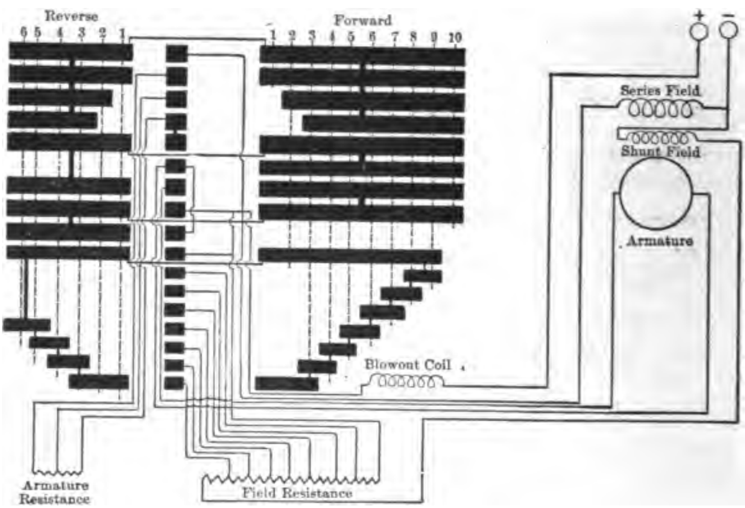


FIG. 497. Connections of a reversible machine-tool controller.

by the controller, and retarded by a dash-pot, shown in the upper right-hand corner of the sketch. This arrangement prevents a rush of current due to the operator passing the first contact too rapidly.

In the "Forward" direction, the motor may be operated both on high and low voltages; the "Reverse" strips are connected to the low voltage only. In most cases it is sufficient to operate the motor in the "Reverse" direction at moderate speeds only.

The blow-out coil shown in both sketches is for the purpose of extinguishing the arc at the finger strip which finally opens the circuit. The coil is connected in series with the main circuit and produces a strong magnetic field in the place where the last contact in the controller is broken. This field shifts the arc outwards, increases its length, and in this way blows it out (Fig. 509).

684. Experimental Controller. — In studying connections and experimenting with an actual controller, the student is handicapped by the fact that the controller is all wired up, and some of the wiring is not accessible. Moreover, the controller is usually intended for a specific duty only, and cannot very well be used for various purposes.

It is therefore advisable to have in the laboratory an *experimental* controller, especially adapted for exercises in wiring. No permanent connections should be made between the strips on the drum, but each strip should be provided with one or more binding posts so that the student may establish any desired connections himself. Some of the

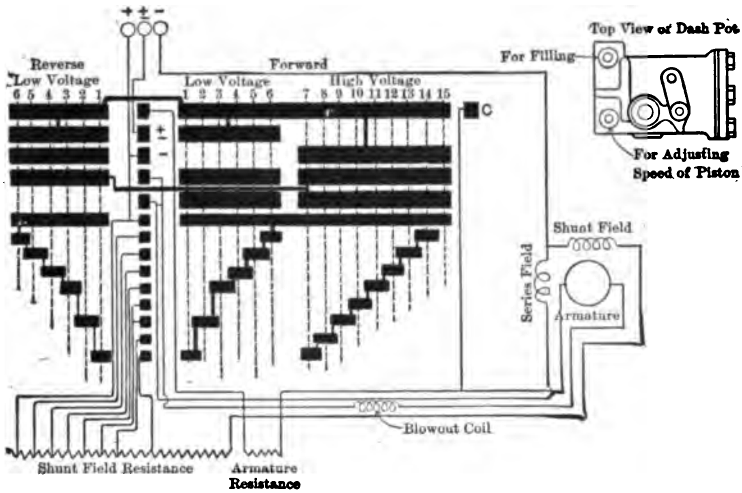


FIG. 498. Reversible machine-tool controller for three-wire service.

strips must be long, others short, and arranged stepwise, for gradually cutting in or out of resistances. Such a controller, if properly designed, is very useful for a study of the operations explained in § 682.

The controller should be mounted horizontally in order to be more accessible, and should have no cover, save that there must be a board on which the fingers are mounted. It is not advisable to have a blow-out coil in connection with it, in order to keep the device as simple as possible. The student should be given an opportunity to study the action of a magnetic blow-out on a separate electromagnet.

685. EXPERIMENT 33-A. — Wiring a Machine-Tool Controller. — The purpose of the experiment is to illustrate the connections shown in Figs. 493 to 498. A special experimental controller should

be used, described in § 684, and the student is supposed to wire up the controller so as to suit certain given requirements. The experiment may be performed in the following order:

(1) Connect up the controller for starting a shunt motor in one direction only, without field control;

(2) Add the necessary connections for regulating the field;

(3) Supplement the scheme by connections for reversing the motor;

(4) Wire up the controller complete for running forward and reverse, on three-wire system.

A shunt-wound motor should be provided, and operated in connection with the controller: this is the best check on the connections. Have an ammeter in the armature circuit, and one in the field circuit; also a voltmeter across the armature terminals. Measure the speed of the motor with various positions of the controller handle.

At the end of the experiment remove all the connections in the controller, so that the next students to use the controller may have the benefit of designing their own connections.

Observe separately the action of a blow-out coil, in a circuit formed with considerable inductance, by interrupting the circuit at a suitable place. At first use a separately excited electromagnet, or a permanent magnet, and observe its action on the arc: Reverse the direction of the main current, also the polarity of the magnet, and in each case notice the effect. Then take a regular blow-out coil, connected in series with the main circuit, and investigate its action. In performing the experiment with the blow-out coil the student must be careful to have the wires well insulated. The e.m.f. of self-induction, when the circuit is opened, may reach several hundred volts and give one an unpleasant shock.

Report. Give the actual connections used and numerical data on the performance of the motor. Describe the experiment with the blow-out coil.

ELEVATOR CONTROLLERS.

686. The essential parts of an electric elevator are shown in Fig. 499. The driving engine may be placed either in the basement or overhead. It consists of a hoisting-drum driven by an electric motor, usually through a worm-gearing (except in very high speed elevators). The car, the counter-weights and the ropes are clearly shown in the sketch, as well as a centrifugal safety device mounted on the top beam. The movements of the car are controlled by a handle in the car, which handle operates the stationary controller shown behind the motor. The controller makes the necessary connections between the motor, the line and the resistances.

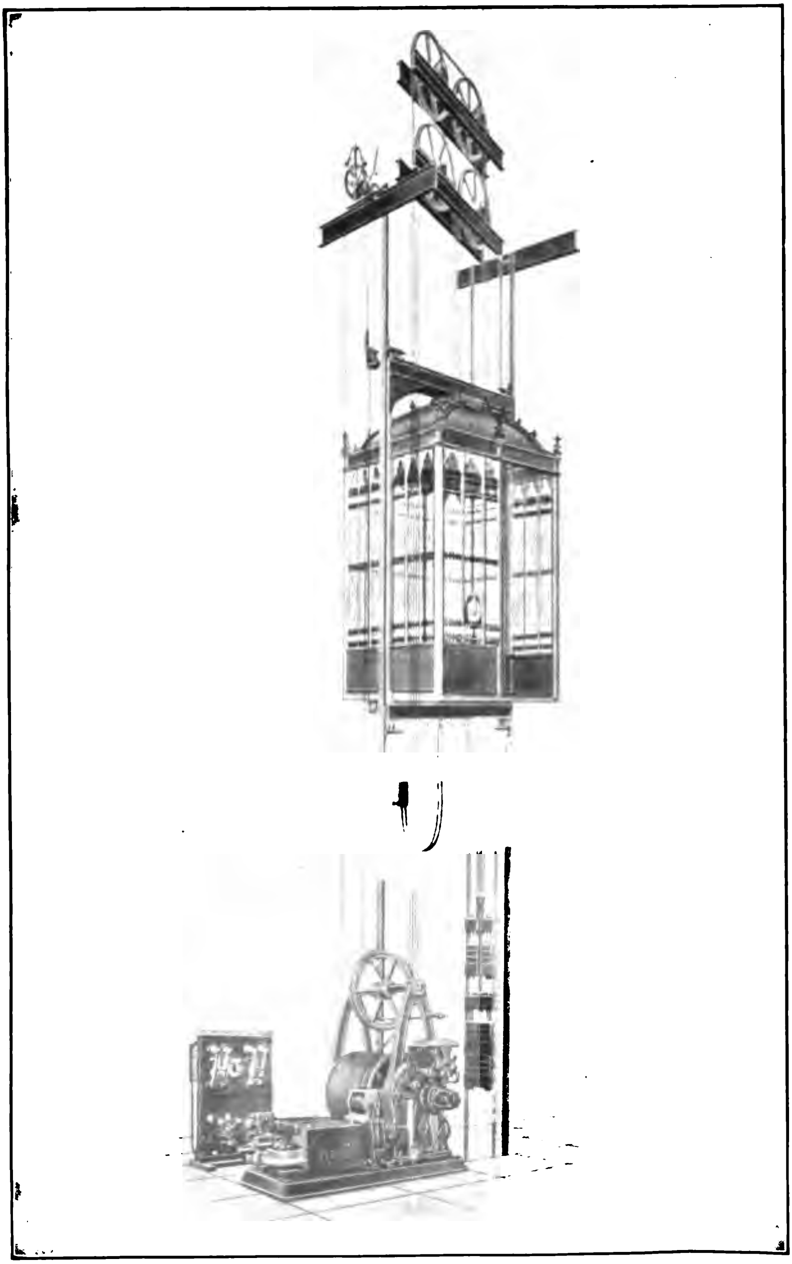


FIG. 499. Otis electric elevator

The motor is provided with a powerful mechanical brake, shown between the motor and the gear-case. The brake is automatically applied when the motor circuit is opened: When the power is "on" the brake is released by a solenoid connected in series with the main circuit. An additional braking effect is obtained by short-circuiting the motor on resistances which make it act as a generator. In large elevators an additional mechanical brake is provided for emergency purposes. The safety devices consist of:

(1) Stop-motion switch.
(2) Slack-cable switch.
(3) Two hatchway limit-switches.

The stop-motion switch is shown in front of the gear-case, mounted on the drum shaft; it automatically cuts off the circuit at the limits of travel, should the operator neglect to do so. The slack-cable switch is an emergency device intended to operate, should the car become jammed in the hatchway while descending. As soon as the drum has slacked off the cable, the switch is opened stopping the motor. The hatchway limit-switches open the main circuit should the car for any reason over-run, either at the top or bottom. These switches operate only in case the "stop-motion" switch on the drum should fail to stop the car, thus constituting an additional emergency device.

The controller operating the motor is actuated from the car either mechanically by ropes, as shown in Fig. 500, or electrically, as in Figs. 499 and 501. The electric control may be either non-automatic (handle control) or automatic (push-button control).

Mechanical control is used only with low-speed (usually freight) elevators. High-speed passenger elevators are provided almost exclusively with non-automatic electric control. Push-button control is used in residence elevators, where no regular operator is kept, and the machine is operated by the passengers themselves; also in so-called "dumb-waiters," or small elevators for carrying goods between floors, when no operator rides with the car.

We shall now describe these three types of elevator control more in detail.

687. Mechanically Operated Controllers. — A representative elevator controller of this type is shown in Fig. 500. It consists of a motor starter shown to the left, and of a combination reversing switch mounted to the right. The motor is heavily compounded, as usual with elevators, in order to obtain a powerful starting torque; at the same time, the shunt winding keeps the speed within reasonable limits. The starter is operated by the motor itself, through a worm-gear and a magnetic clutch, visible on top of the sketch. The reversing

switch is operated by a rope from the car; it has three positions: "off," "up," and "down."

Assuming the car to be at rest, when the operator pulls on the rope in a certain direction, first the reversing blades of the switch connect the motor armature so as to run in the proper direction, then the line contact to the left is closed through the segmental ring, and finally the

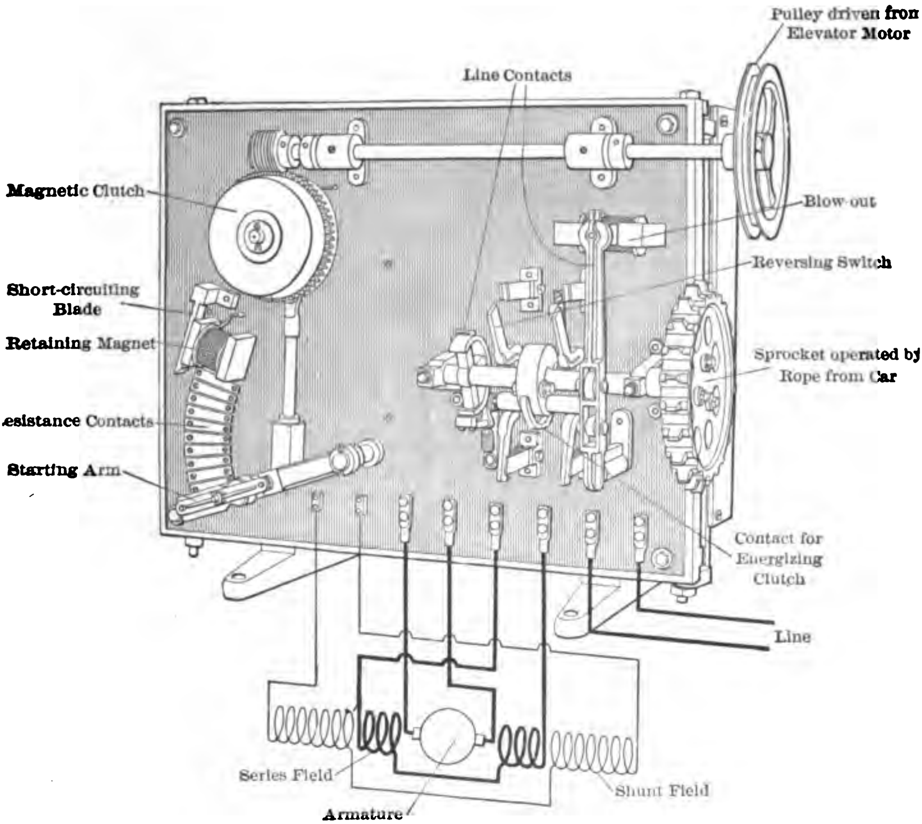


FIG. 500. Mechanically operated elevator controller (The Automatic Switch Co.).

other side of the line is closed by the carbon contact between the poles of the blow-out. The motor starts with all the resistance "in."

At the same time the contact ring on the shaft of the switch closes the circuit of the magnetic clutch, and energizes it. The horizontal shaft, shown on top of the controller, is belted to the motor, and begins to rotate as soon as the motor starts. When the clutch is energized, the shaft is mechanically connected with the starting arm, which begins to move upward, gradually cutting out the starting resistance.

When the starting arm touches the contact marked "Short-circuiting blade," it bridges the clutch and deënergizes it. The arm is held in the upper position by the retaining magnet, as in ordinary starters, such as in Fig. 303. The clutch is deënergized so as to prevent wear due to friction: one part of it continues to revolve as long as the motor is running. Opening the main switch deënergizes the retaining magnet, and the starter arm drops by gravity.

The sprocket wheel operating the main switch is also connected to the automatic limit device on the winding machine. In this way it is not only actuated by the operator to start and to stop, but is also automatically opened, as soon as the car approaches the limit of travel in either direction.

The actual electrical connections on the back of the face plate may be easily understood from the above description of the parts and the functions of the controller.

688. EXPERIMENT 33-B. — Study of Mechanically Operated Elevator Controllers. — In performing this experiment it is advisable to have the controller and the hoisting engine disconnected from the elevator car, so as to operate them separately. This is safer for the beginner, and also more profitable, since combinations may be tried, impossible when the car is in motion. An elevator car can be entrusted only to a mature and experienced person. The necessary load on the hoisting engine is obtained by putting a Prony brake on the drum, or on a pulley mounted by its side. Perform the experiment in the following order:

(1) Wire up the controller and the motor, as per blueprint, which usually accompanies the controller; also study the permanent connections.

(2) Put current through some of the controller circuits, without allowing the motor to revolve: make sure that the clutches, the brake, the retaining coil, etc., operate properly.

(3) Start the motor, and adjust the regulation so as to obtain the lowest possible speed.

(4) Observe the operation of the "limits" and of the safety devices in the elevator shaft, and on the machine itself.

(5) Take a few readings with the motor running at different loads, and also when starting and stopping. Read current, speed, e.m.f. across the brushes, seconds time necessary for the operation of controller parts, action of the brake, etc.

689. Non-Automatic Electric Control. — Controllers operated electrically by a master switch in the car are shown in Figs. 499 and

501. Such controllers consist of individual electromagnets, which, being energized, close the line and the motor circuits in the required order. The functions of the different parts of the controller shown in Fig. 501 are as follows:

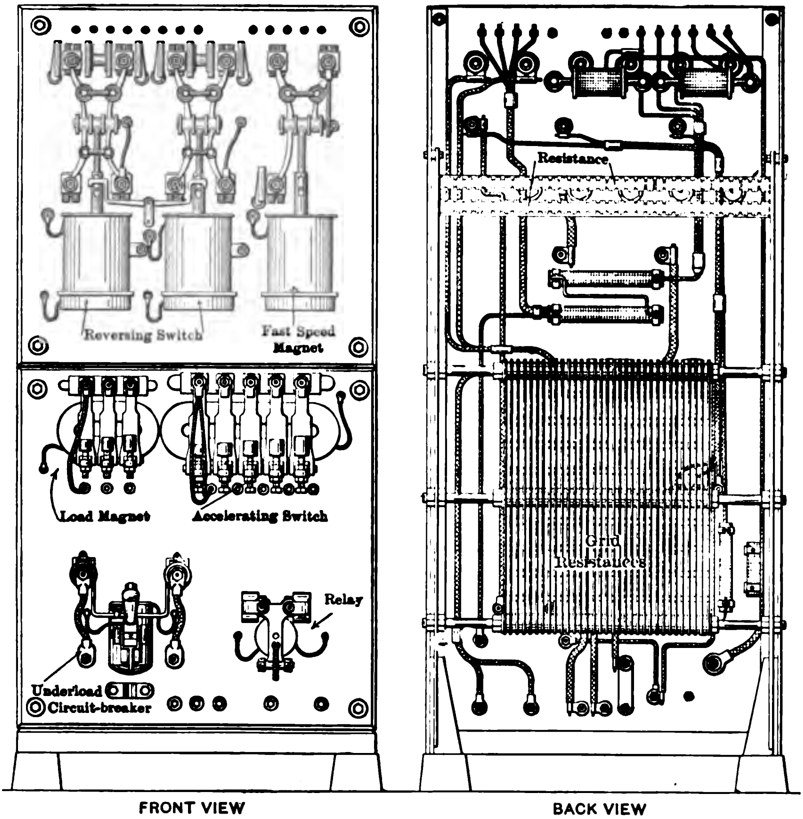


FIG. 501. Electrically operated elevator controller (front view and back view).

Upper row: The two solenoids to the left close and open the main line-circuit and connect the armature of the motor for the "up" or "down" motion of the car. The solenoid to the right is open with the low speed of the car, and is energized when the car switch is moved in the position corresponding to the high speed.

Middle row: The right-hand magnet with five contacts is the accelerating switch, which automatically short-circuits the starting resist-

ance in steps: The magnet to the left, with three armatures, is the so-called "load magnet." It automatically brings the car to a stop at the top and bottom landings at the same point, independent of the load of the car.

Lower row: The switch to the left is an underload circuit-breaker, or, as it is called in this case, a potential switch. The coil which holds it closed is connected across the main line, and in its circuit are connected several switches which act as safety devices. Should trouble develop, the switch flies open and breaks the main circuit. The small magnet to the right is a relay switch, which establishes contacts for the load magnet and for the magnetic brake of the machine.

The motor with which this controller is intended to be used is heavily compounded, as in Fig. 500, and in addition has an "extra" shunt-winding which is operative on the low speed, and when stopping the car. The car switch has two positions for both "up" and "down" directions: One contact is for the low speed, the other for the high speed of the car. The operation of the controller is as follows:

Consider the car somewhere in the middle of the hatchway and the car switch in its zero or center position. No coils on the controller are energized, except that of the potential switch: this switch remains closed all the time as long as the elevator is in regular operation. The first movement of the car switch energizes either the "up" or the "down" coil on the reversing-switch in the upper right corner of the controller: the armature of the motor is thereby connected to the line, in the desired direction. The closing of the armature circuit also excites the brake coil at the motor and releases the brake. The motor and the car are set in motion.

Now the accelerating magnet (second row, to the right) is brought into play: Its magnetizing coil is connected across the armature terminals, and, as the counter-e.m.f. of the motor increases, the several arms of the magnet are operated one after another, short-circuiting the starting resistance. Finally the series field is also short-circuited, and the motor continues to run with the shunt winding only. The magnet armatures are set at different distances, so that they respond in succession to the gradual increase of the potential of the armature. The second movement of the car switch energizes the slow-and-fast-speed magnet, in the upper right-hand corner, with the result that the upper contacts of its switch short-circuit some resistance in series with the motor armature, while the lower contacts open the circuit of the "extra" shunt field. The field of the motor is thereby weakened, while the voltage at its terminals is increased. The car is accelerated to its full speed, either up or down.

The first movement of the car-switch handle from the full running position towards the stop or center position, interrupts the circuit of the slow-and-fast-speed magnet, and the "extra" field is again inserted in the circuit, as well as some additional resistance in series with the armature: This brings the motor to a lower speed. The second movement of the car switch, which brings it to the center, interrupts the reversing-switch circuit, thereby interrupting all of the controller circuits, with the exception of the potential switch. This cycle of operations may be performed as often and as quickly as necessary.

The potential switch is equipped with an auxiliary contact, to which is connected one side of the brake circuits; this allows the brake solenoid to become deënergized the instant the potential switch is opened. Thus, when the safety switch in the car, the extreme hatchway limits, or the slack-cable switch are opened, deënergizing and opening the potential switch, the brake has its current instantly cut off, and becomes operative. At the same time, when the potential switch flies open, it connects across the armature terminals of the motor a "stop resistance." The motor acts then as a generator, and this braking effect aids in bringing it quickly to a stop.

The "load" magnet in the middle row, with three armatures, permits stopping the car at the top and bottom landings at exactly the same point, independent of the magnitude of the load. This is important, since elevators are generally installed with very small overhead room, and very small pit room: Care should be taken therefore to prevent a possibility of running into the overhead work, or against the bottom. This is a serious problem with high-speed elevators, since the load makes a considerable difference in the speed and distance in which the car can be brought to rest. The above load magnet solves this difficulty in the following way:

As the car nears the top or bottom landing, it opens a switch, which introduces some resistance in series wth the armature, and a high resistance in parallel to the armature. The motor slows down and varies its speed according to the load, because of the resistance in series. The heavier the load or the armature current, the larger is the drop in the resistance, consequently the lower the voltage at the armature terminals. After this load variation of speed has had time to establish itself, a second circuit is closed automatically which energizes the coil of the three-contact "load" magnet. According to the load, or to the potential resulting from the speed of the motor, more or less of the load magnet armatures are pulled in, short-circuiting more or less of the resistance in parallel to the motor armature. The retarding effect

resulting from this consequently depends upon the load: the heavier a descending load, the more contacts are closed, the greater is the reduction in the resistance of the parallel circuit, and the greater is the reduction in speed. By providing a sufficient number of contacts on the load magnet, any desired exactness of automatic stop for different loads can be attained.

690. EXPERIMENT 33-C. — Study of Electrically Operated Non-Automatic Elevator Controllers. — See § 688 for directions.

691. Automatic Electric Elevators (Push-Button Control). — Automatic control of elevators is used in places in which a limited use of the elevator does not warrant keeping a special attendant, as, for instance, in residences. Automatic control is also used in the so-called "dumb-waiters," or small elevators intended for carrying goods between the floors of a store or a factory. A bank of push buttons is provided on each floor, and also in the car, if it is intended for passenger service. Each bank consists of as many buttons as there are floors; an extra "stop" or emergency button is also provided.

Thus, if a person on the second floor of a building wishes to send something to the fourth floor by means of the dumb-waiter, when the car is at rest on the first floor, he presses the button No. 2; this closes an auxiliary circuit on the controller, which in turn starts the elevator motor. The car is brought to floor No. 2 and automatically stopped there. The person opens the hatchway door, loads the car, closes the door again, and presses button No. 4. This sends the car upward to the fourth floor, and it stops there automatically opposite the hatchway door, without any further attention on the part of the person who has sent it.

The controller is, in its principle, similar to that described in § 689: it also consists of unit switches, each performing a specific duty. The switches are closed by solenoids, operated by the push-buttons. When the car arrives at the desired point, the solenoid circuit is automatically opened by the "stop-motion" device, which is connected mechanically to the motor. A detailed description of circuits used by different companies would be out of place here; each controller is accompanied by a blueprint of its connections and by detailed instructions for wiring and operation. The understanding of these diagrams may be assisted by keeping the following points in mind:

(1) The push-button circuit is closed through all the hatchway doors and the car door in series, so that the car cannot be started unless *all* the doors are closed. This is an important precaution for the safety of those using the elevator.

(2) A "stop" or emergency button is always provided; pressing this button instantly stops the car in whatever position it happens to be. After this its destination may be changed by pressing the corresponding push-button.

(3) After having pressed a button it is not necessary to hold it until the car ends its travel: as soon as the corresponding floor solenoid on the controller is energized, it closes not only the main circuit, but also an auxiliary contact, which keeps the solenoid circuit closed, around the push-button.

(4) The push-buttons, and the solenoids which they operate, are so interconnected that when one of them is in operation no other circuit can be closed, until the car has finished its travel.

(5) If two push-buttons are pressed at once neither solenoid operates. This can be accomplished, for instance, by having a resistance in series with the push-button circuit: when two push-buttons are pressed down the voltage drop in this resistance becomes so large, that the current is no longer sufficient for operating the solenoids.

The most important features of the power circuit are the same as with non-automatic controllers: When the main circuit is closed the magnetic brake is automatically released. The motor starts as a compound-wound machine; when a certain speed is reached, an accelerating magnet gradually short-circuits the starting resistance, and finally the series winding. When the main circuit is opened, the brake is automatically set.

692. EXPERIMENT 33-D. — Study of Push-Button Operated Elevator Controllers. — For directions see § 688.

CHAPTER XXXIV.

ELECTRIC RAILWAY WORK.

693. EXPERIMENTS and devices described in this chapter are intended to illustrate certain features peculiar to the operation of electric railways. At the same time it is believed that the principles involved are of sufficient interest to warrant the experiments being performed by the general student of electrical engineering. The subject-matter is treated under four headings:

(1) Drum-Type Electric-Car Controller;
(2) Multiple-Unit Control of Trains;
(3) Acceleration and Retardation Tests on Cars;
(4) Air-brakes.

1. DRUM-TYPE ELECTRIC-CAR CONTROLLER.

694. The street-car controller (Fig. 502) accomplishes electrical connections necessary for starting the car, stopping it, and varying its speed. All these operations are performed by the motorman, by simply turning the handle through a certain number of positions, or "notches." The use of the controller is made as simple as possible, so that the motorman may devote most of his attention to the road and to signals.

The principal parts of the controller are two revolving drums: The large drum to the left is for starting and speed control; the small one to the right, for reversing the motors; each drum is provided with an operating handle. The drums are provided with copper strips which rub against stationary contact fingers. The fingers are connected to the motors, resistances, trolley, ground (car truck), etc. In different positions of the drum, various fingers are connected by the strips on the drum in different combinations, so as to produce the desired control.

The other parts of the controller shown in the cut, are: a blow-out coil for extinguishing the arc, cut-out switches for disconnecting a disabled motor, an insulating frame with partitions, and the cover.

695. Operating Features of the Controller. — The electrical connections in a controller may be best understood from the functions which it is obliged to perform. Electric cars are usually equipped with

two or four series-wound motors; in the latter case the two motors of each truck are permanently connected in parallel, and for the purposes of regulation may be considered as one motor. In starting the car, the armatures of the motors, their fields, and some additional resistance are all connected in series, in order to limit the rush of current. As the car acquires speed, the starting resistance is gradually cut out, because the counter-electromotive force of the motors prevents an excessive

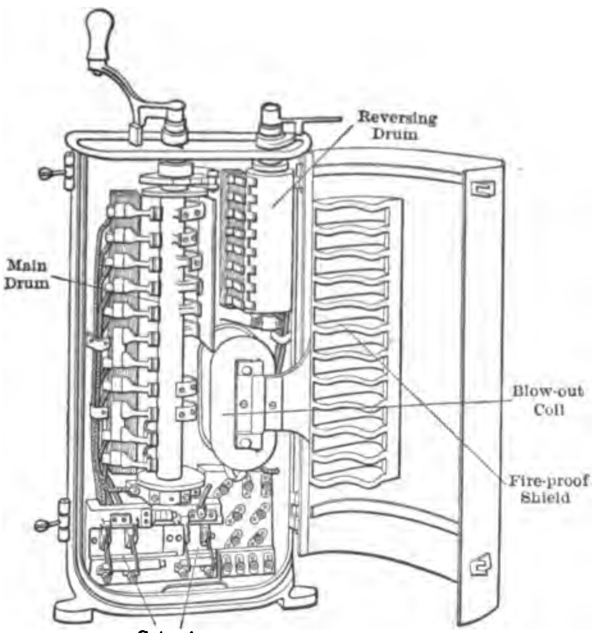


FIG. 502. Electric car controller.

rush of the current from the line. When all of the resistance is cut out, the two motors run in series *at half speed,* for, if the line voltage is 500 volts, each motor has only 250 volts at its terminals (Fig. 503). To increase the speed, the motors must be connected in parallel, so that each has 500 volts pressure at its terminals. Before this is done, some starting resistance is again inserted into the circuit, to avoid a sudden jerk and a rush of current in changing from half speed to full speed. Then, as the car goes faster and faster, this resistance is again gradually cut out, until the two motors are connected directly across the 500-volt line in parallel, and the car runs *at full speed* (Fig. 504).

In stopping the car, the motorman first shuts off the power and then applies the brakes. Three kinds of brakes are in use at present: hand brakes, air brakes, and magnetic brakes. Each car is necessarily provided with a hand brake, either for regular service or for emergency. Cars in large cities, high-speed suburban and interurban cars, cars running on roads with long and steep grades, etc., are provided in addition with air-brakes (described below, beginning with § 716). On a few electric roads the so-called *magnetic* brakes are used (§ 704).

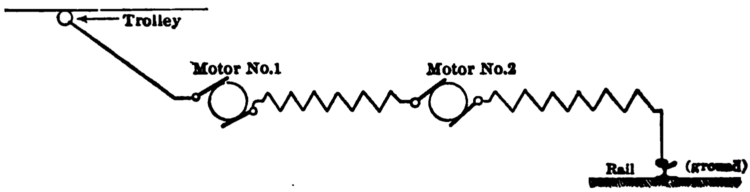


FIG. 503. Motors in series.

Thus, the controller must give two principal combinations of the motors, — in series and in parallel. For each of these combinations intermediate positions are provided, with more or less resistance in the circuit. A complete diagram of connections in a street-car controller, with all details, including a magnetic brake, is shown on the folded plate below. But, before attempting to follow in detail this comparatively complicated system, the student should clearly understand the three simple diagrams shown in Figs. 505, 506, and 511.

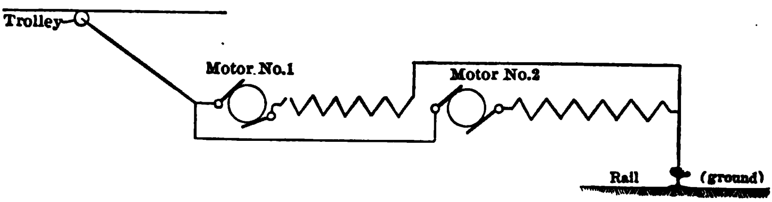


FIG. 504. Motors in parallel.

The complete diagram is a combination of these three schemes: as far as possible, the same letters are used in the elementary diagrams as in the complete diagram.

696. Connections for Starting. — In describing controller connections it is customary to develop the drum and to indicate the positions of the motorman's handle by vertical dotted lines, as shown in Fig. 505. In this way the connections for any position of the controller may be easily followed out on paper. The connections for starting the car, with the motors in series, are shown in Fig. 505.

When the controller handle is on the first notch, the row of fingers T, R_2, E_1 and A_2, touch the drum contacts along the vertical dotted line 1. The path of the current is as follows:

The current from the trolley flows through the circuit-breaker $C.B.$ to the contact finger T and thence through the strips a_1 and a_2 to the finger R_2. Since the fingers R_4, R_5, and R_6 do not touch the corresponding strips a_3, a_4 and a_5, the current flows through the whole resistance R_2R_6, through motor No. 1 to the finger E_1. Thence through b_1 and b_2 to motor No. 2, and finally to the ground G.*

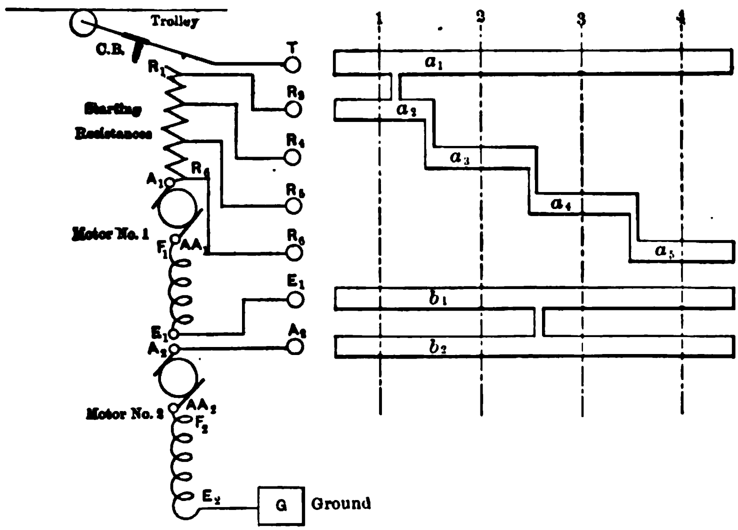


FIG. 505. Controller connections with motors in series.

On the second notch the current finds a shorter way from T through the strips a_1, a_2, and a_3 to the contact finger R_4, so that part of the resistance between R_2 and R_4 is cut out; in other respects the current follows the same path as before. On the third notch the contact R_5 becomes operative; finally, on the fourth notch the current from T follows directly through a_1, a_2, a_3, a_4 and a_5 into the armature of the first motor, and the whole resistance R_1R_6 is cut out of the circuit: this gives the *full series* (half-speed) connection.

(*) Only *one* wire (trolley wire) is used in electrical-railway circuits, the current returning to the generating station (or substation) through the rails; the ground on the car is obtained by connecting the wire G to the truck. The current flows through the truck, axles, and wheels, to the rails; one of the bus-bars in the station is also connected to the rails.

Positions 1, 2 and 3 are called the "resistance points"; 4 is the "running" position. The motorman is not allowed to ride for any length of time on these "resistance points," but must use them for starting only. The starting resistances, used on cars, are not large enough to be permanently connected into the circuit; they would get excessively hot and burn out in a short time.

It is well to remember that a diagonal chain of contacts on a controller diagram, such as a_2, a_3, a_4, a_5, usually signifies a gradual cutting in or out of resistances.

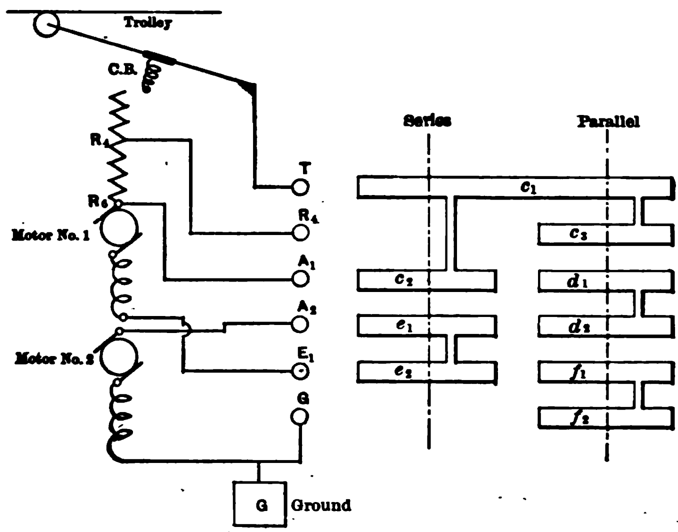


FIG. 506. Change from series to parallel.

697. Change from Series to Parallel.—To change from half speed to full speed the motor connections have to be changed from series to parallel, and some resistance temporarily introduced into the circuit. The controller fingers and strips that are operative in this change are shown in Fig. 506. With the motors in series, the current from the trolley finger T flows through c_1 and c_2 into the first motor; then through e_2 and e_1 to the second motor, and to the ground. On the first "parallel" notch the current from T, through c_1 and c_3, flows to the resistance R_4R_6, and then *is divided* into two halves: One half follows the path — motor No. 1, E_1, f_1, f_2, G, to the ground; the other half — finger A_1, d_1, d_2, A_2, motor No. 2, to the ground. On the next notches (not shown) the resistance is gradually cut out, until the motors are in "full parallel."

This change involves breaking the circuit; as the connections are changed hundreds of times during the day, the resulting sparks would quickly deteriorate the fingers. Therefore, intermediate points are provided for changing from series to parallel, without opening the circuit. The principle is shown in Fig. 507: The upper line (*a*) represents the connections on the last notch, with the motors in series and the resistance short-circuited; the last line (*e*) corresponds to the first

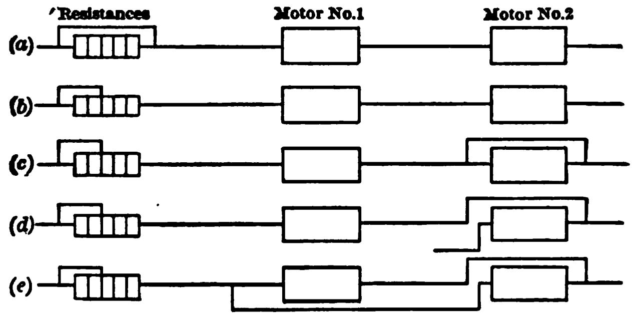


FIG. 507. Change from series to parallel without opening the circuit.

parallel position, same as in Fig. 506. The intermediate connections are shown on the three sketches (*b*), (*c*) and (*d*) between these: First, some resistance is introduced into the circuit; then motor No. 2 is short-circuited (or, which amounts to the same, motor. No. 1 is grounded around it). After this, the circuit of the second motor is opened, and the connections changed from series to parallel. These changes are made in the positions 6 to 8 of the controller handle (see

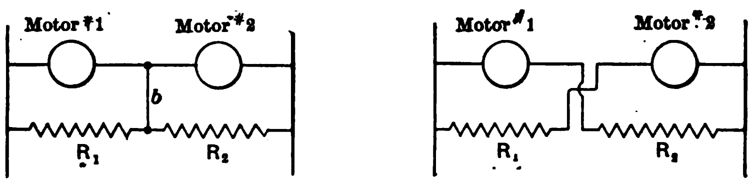


FIG. 508. "Bridge" method for changing from series to parallel.

folded plate). These positions are called transition points, and the motorman should pass them without stopping.

698. Bridge Connections. — The above method of changing from series to parallel has a disadvantage that the current, and consequently the torque of the motors, change suddenly, producing an unpleasant jerk during acceleration. This is obviated in the so-called bridge connection recently put into practice. The principle of the bridge connection is shown in Fig. 508: The sketch to the left corresponds to

the last notch with the motors in series; the sketch to the right gives the connection on the first notch with the motors in parallel. After all the resistances have been short-circuited and the motors are connected in series across the line, two equal resistances, R_1 and R_2, are connected across the line. The value of the resistances is such that they take about the same current as the motors. This doubles the current taken from the line, but does not affect the torque of the motors, which are in a separate circuit. Now the bridge connection *b* is established between the motors and the resistances: No current flows through this bridge, both its extremities being at the same potential. With this bridge, motor No. 1 and the resistance R_2 may be considered as one circuit, and motor No. 2 with the resistance R_1 as another circuit. Separating these two circuits gives the diagram shown at the right. The motors are now connected in parallel, with some protective resistance in series with each. The change is accomplished without breaking the circuit, and with practically no change in current through the motors, since hardly any current flows at first through the bridge *b*.

Bridge connection is used on large cars, especially those provided with multiple-unit control (see § 707): with this arrangement, no jerk is felt during the change from series to parallel, and starting is accomplished smoothly, even with high rates of acceleration.

699. Other Features of the Drum Controller. — The connections described above are incorporated in the complete diagram of the controller shown on the folded plate. A glance at this diagram will show, however, that the connections are more complicated than a mere combination of the series-parallel control. The complications are caused by the addition of the following parts:

(1) A reversing drum for backing the car.

(2) Cut-out switches for disconnecting a disabled motor.

(3) Blow-out magnet for extinguishing electric arcs.

(4) Contact points for shunting motor fields, to obtain a higher speed.

(5) Contact points for magnetic brake.

In addition to these, the requirements of construction and insulation necessitate a somewhat different disposition of the controller fingers and of the drum strips, than that described above. However, keeping in mind the above two fundamental schemes (Figs. 505 to 507), the following up of the actual connections will hardly offer serious difficulties.

The five above-enumerated features are taken up below, more in detail.

700. Reversing the Motors. — The motors are reversed by interchanging the armature leads; the shorter drum shown to the right, in Fig. 502, is provided for this purpose. The development of this drum is shown in the upper part of the large diagram (folded plate), to the right of the development of the main drum. The reverser is, in principle, an ordinary double-throw switch. The leads A_1 and AA_1 come from the terminals of the armature of motor No. 1; terminal 12 is connected to one end of its field winding, terminal 20 to the resistances. In the "forward" position of the reversing drum, terminal 12, or the field of motor No. 1, is connected to AA_1, while terminal A_1 is connected to terminal 20, or to the resistances. In the "reverse" position of the drum, terminal 12, or the field of the motor, is connected to A_1, while AA_1 is connected to 20, or to the resistances. The connections are identical in the two cases, except that the armature leads are interchanged. Similar connections are provided for the other motor, by means of the fingers 11, AA_2, A_2, 17 (see also Fig. 495).

A reversing drum is not supposed to be operated with the power "on"; for this reason no blow-out coil is provided. The two controller handles (Fig. 502) are so interlocked mechanically, that the reverser can be operated only when the regulating handle (the left-hand handle) is in its "off" position. Thus the motorman is forced to first open the circuit by means of the regulating handle, before he can reverse the motors. Moreover, the interlocking is such, that the regulating handle cannot be moved when the reverser is in its middle or "off" position. It is easy to see that without this feature, the interlocking would not be complete.

A third feature of interlocking is that the reversing handle cannot be removed, except in the "off" position. When the motorman leaves the car, he is supposed to take this handle with him. To do so, he has first to bring his regulating handle to the "off" position; only then can he turn the reverser drum into the neutral position and remove the handle. All the circuits are thus broken, and no one can start the car, except by having an identical handle.

701. Cut-Out Switches. — Switches for disconnecting a disabled motor are shown at the bottom of Fig. 502; in the folded plate they are shown below the reversing drum. It will be seen from the diagram of connections that if motor No. 1 is disabled and the motorman opens the corresponding switch, a by-pass is offered to the current through the auxiliary contact marked "3 and R_6" to motor No. 2, while the field, the armature and the shunt circuits of the disabled motor are opened. If motor No. 2 is disabled and its switch opened, a by-pass to the ground for the other motor is offered by the auxiliary contact

G, behind the switch, while the field and the armature circuits of the disabled motor are opened.

702. Blow-Out Coil. — The blow-out coil is shown in Fig. 502 below the reversing drum. It is intended for blowing out the electric arc between the controller fingers and the drum strips, every time the circuit is broken. Its application is based on the fundamental fact (Fig. 509) that an electric current, being placed in a magnetic field, tends to move *across* the field; in other words, so as to cut the lines of force. The pole-pieces *MM* are placed so that the lines of force are

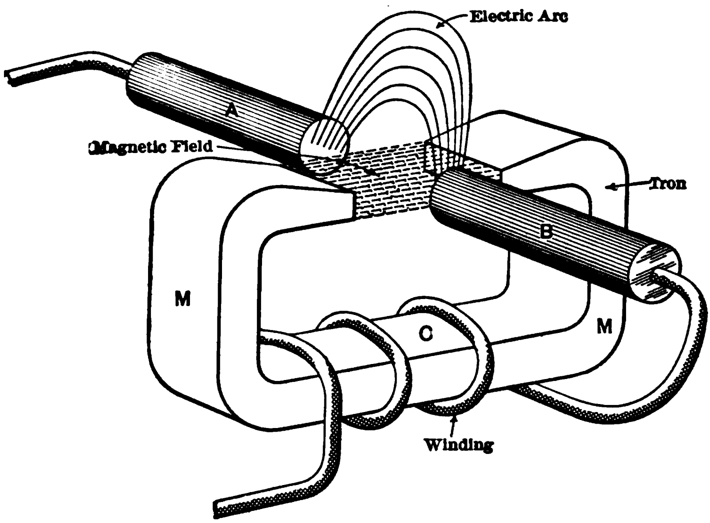


FIG. 509. The action of a magnetic blow-out.

perpendicular to the direction of the arc between *A* and *B*, and tend to move the arc outside, increasing its length and finally rupturing it. The blow-out coil is one of the most essential parts of the controller: it must be remembered that the circuits of a street car are broken thousands of times a day, and without a blow-out arrangement the sparks would deteriorate the contacts in a very short time.

The coil of the blow-out magnet is usually energized in series with the line, so that its action is stronger the heavier the current to be ruptured. In the folded plate, the blow-out magnet is shown in the lower left-hand corner. It will be noted, that in this case the coil consists of two sections, one operative when the power is "on," the other when the magnetic brakes are applied.

703. Shunting Fields. — The speed of direct-current motors may be increased by weakening their fields (§ 251); in series motors this is done by shunting the fields by certain resistances. This method had been used in the earlier days of electric traction, but has been abandoned of late years on account of sparking at the commutator, due to weakened field. However, with the advent of the compensated motor (§ 262), in which the armature reaction is greatly reduced, shunting of fields is coming into use again.

Two positions with fields shunted, are provided in the controller, shown on the folded page: Position No. 5 is that with the motors in series, position No. 12 with the motors in parallel. The shunting resistances are permanently connected to the motor fields on one side, while the other ends of the resistances are connected to the controller fingers L_1 and L_2. In the positions Nos. 5 and 12 these fingers become operative, closing the shunts and thereby weakening the fields of the motors.

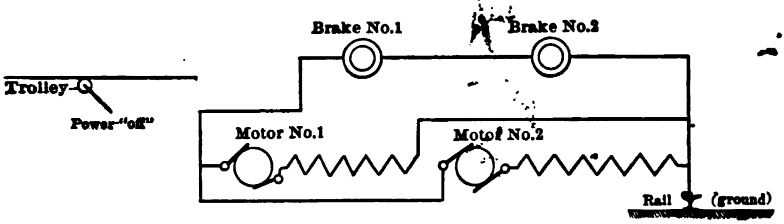


FIG. 510. Connections with magnetic brakes "on."

704. Magnetic Brakes. — The principle of magnetic braking is substantially as follows (Fig. 510): The motors are disconnected from the trolley line, and their fields and armatures are connected in such a way that they act *as generators*, utilizing the acquired momentum of the car for supplying the energy necessary for producing current. The car is provided with brake shoes made in the form of electromagnets, which are placed either near the rails or near iron disks mounted on the axles. When the current, generated by the motors, is sent through these electromagnets, they become energized and press themselves against the rails, or the disks on the axles, producing a powerful braking effect. The intensity of braking is regulated by the amount of resistance in the circuit.

Formerly a method of electric braking was used, which consisted in closing the motors, acting as generators, on resistances, in which the stored energy was dissipated in the form of heat. This method of braking has been abandoned, because it is liable to overload the motors: they have no time to get cooled off, even while the car is coasting down a long grade.

Controller connections for magnetic braking are shown in Fig. 511. The two motors are connected in parallel by the strips i_1 and i_2 on one side, and by h_2 and h_3 on the other; the current generated in both motors flows through h_1 and the resistances R to the strip g_1 and thence through the contact-finger B to the brakes; the circuit is completed through the ground G. The three positions shown in the sketch differ only in the amount of the resistance R in the circuit. Brake connections on the large diagram will be understood from this simple scheme.

There are two more points to be noted:

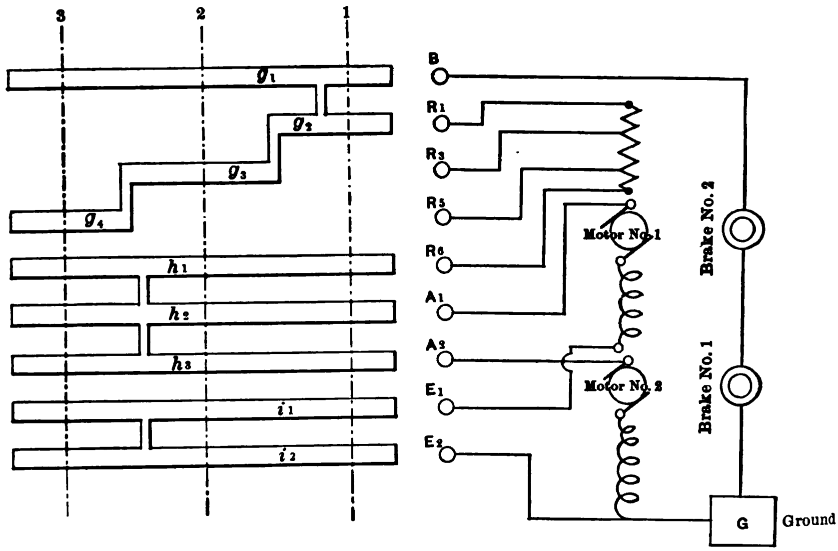


FIG. 511. Controller connections for magnetic brakes.

(1) *The brakes must be demagnetized* before power is put on, because of residual magnetism which keeps them attracted, even after the current has been shut off; therefore, additional contacts B and DR (" brakes " and " demagnetizing resistance ") are provided on the first power notch. By means of these contacts, a small current is sent through the brakes in the direction opposite to that in which they are usually magnetized. This destroys the residual magnetism, and the brakes are released. The corresponding scheme of connections is shown separately in the lower right-hand corner of the sheet.

(2) *A current-limiting electromagnet* is connected into the brake circuit, as shown in the lower left-hand corner of the diagram. When the braking current rises beyond a certain limit this electromagnet closes the limit switch which short-circuits the fields of the motors:

this reduces the main current, and the electromagnet again releases the switch. No circuit-breaker or fuse could be used for this purpose, because the device must be *self-restoring.*

705. Acceleration Limit. — In order to prevent the motorman from moving the controller handle too fast at the start, special devices are sometimes used, which limit this speed to a certain predetermined value. A simple apparatus of this kind, the so-called "Automotoneer," is based on the pawl-and-ratchet principle; every time, after the motorman has moved the handle by one notch, he has to give it a slight backward movement in order to release the "dog." This makes it impossible to move the handle above a reasonable speed.

In another device, the handle is connected to the controller drum through a heavy spiral spring. By moving the handle the motorman winds up the spring, but the motion of the drum is retarded by a dash-pot, which may be set to operate at any predetermined speed. The motorman may thus throw his handle at once around to the last parallel position without affecting the speed at which the drum follows it.

A third method is to regulate the speed of the controller drum by a current relay. The drum is governed by a magnetic clutch operated by a relay, having its coil connected into the main circuit. The clutch holds the drum until the current has fallen to a predetermined value, after which the drum is allowed to go to the next notch.

It is claimed that considerable economy in power consumption, and a better schedule, are obtained by using the above-described devices, since they limit the rush of current at the start and permit of a more uniform acceleration.

706. EXPERIMENT 34-A. — Operating an Electric-Car Controller. — The laboratory equipment for this exercise should consist of a regular drum-type series-parallel controller, and of two street-car motors which may be connected to it. It is well to have the two motors either belted or direct-connected to each other, in order to make them run at the same speed.

It is hardly feasible to operate this equipment on a 500-volt circuit, because the motors, having no load, would run away. The performance of the controller is studied just as well on an ordinary 110-volt circuit, at which voltage 500-volt motors run at a moderate speed even at no load.

The student is expected to connect up the controller to the motors and to the power supply, and to operate it as if it were on an actual car. A blueprint of connections usually accompanies each controller. The connections may be different from those shown on the folded plate,

but with a clear understanding of the above diagram and of the principles explained in §§ 694 to 705 the student will find no difficulty in understanding the connections in any street-car controller.

The points to which particular attention should be paid during the operation are:

(1) Interlocking of handles.

(2) Disconnecting a disabled motor

(3) Operation of the blow-out coil.

Report. Give the actual diagram of connections, or at least any parts of it which are different from those described above. Explain the mechanical details of the interlocking devices. Describe peculiarities, if any, observed in the operation of the controller and of the motors.

2. MULTIPLE-UNIT CONTROL OF TRAINS.

707. As long as electric cars were operated singly, the ordinary hand-operated drum-type controller, described above, was entirely satisfactory. But with the advent of electric trains, such as are operated on elevated, underground, and some inter-urban roads, new problems of car control presented themselves. The first electric trains consisted of one motor car and several trailers, as on steam roads, but this method was soon found objectionable. Not only is the acceleration obtained too low for fast service, but the trailers cannot be operated separately during the hours of small traffic, thus depriving the electric system of one of its great advantages, — flexibility.

It was soon perceived, that the right solution was to have trains consisting of *several motor-cars* operated by a motorman from the front car. This brought up the question of controllers by which all cars on the same train could be operated simultaneously, or each car be used separately, if so desired (Fig. 512). It would not be practicable to carry heavy electric currents through the train and to distribute them to different motors; each car must collect its own current through a trolley, or through contact shoes from the third rail. Therefore, each car must have its own controller, operated by some electrical or mechanical means by the motorman on the front car.

Two sources of power are available for such control: electric power from the line, and compressed air stored for the brakes. The first method is used by the General Electric Co., the second method by the Westinghouse Electric and Mfg. Co. This system of control, with which each car is a separate unit, and at the same time any number of cars may be operated in multiple, is called the *multiple-unit control.* The controllers themselves do not need to be in the form of a drum, since they are not operated by hand. They usually consist of separate

"contactors" or "unit switches" (Fig. 512) which are closed and opened either by electromagnets, if electric control is used, or by stems of pistons, in the pneumatic control. In either case, auxiliary wires are provided, running through the train and controlled by the motorman.

In the system used by the General Electric Co., the auxiliary circuit is supplied from the line, and it energizes the operating solenoids of the contactors. In the Westinghouse electro-pneumatic control, the valves which admit compressed air into the contactor cylinders are operated electrically. The necessary current is supplied from small 14-volt batteries, through the auxiliary wires running through the train.

708. Principles of Operation of a Multiple-Unit Controller. — The principle of operation of a General Electric multiple-unit controller may be gathered from Fig. 512. There are two distinct circuits, both fed from the trolley: the power circuit is shown by heavy lines, the control circuit is shown by light lines. Two motor cars of a train are shown, the motorman being supposed to be on car No. 1.

To simplify the explanation of the principle of the control, each car is assumed to have but one motor, with but three positions of control: (1) Circuit open, (2) circuit closed through the starting resistance, and (3) the motor connected directly to the line. When the contacts at *A* and *B* are open, the motor circuit is open; closing the contactor *A* sends a current through the motor, in series with the starting resistance; when the contactor *B* is closed, the resistance is short-circuited and the motor connected directly to the line.

The contactors *A* and *B* on all the cars of a train are operated from two train wires, either of which may be energized from the master controller, operated by the motorman. In the position of the master controller, shown in the diagram, all the circuits are open. When the controller drum is moved to the position 1, the upper train wire is energized, causing the operation of the contactors *A* throughout the train. When the master controller is moved to the position 2, the lower train wire is also energized; the contactors *B* are closed on all cars. Returning the master controller to its zero position opens all the contactors. With this arrangement, a train consisting of any number of cars may be operated by the master controller of any car; at the same time each car may be operated singly, if so desired.

Two contactors only, on each car, are shown in Fig. 512; in reality the connections are much more complicated, because about 15 contactors are required on each car in order to perform all the necessary connections for starting two or four motors, gradually cutting out resistances, changing from series to parallel, and reversing. It would lead to needless complications to give here a complete diagram of

connections for a multiple-unit controller. Moreover, such a diagram would be of little practical value, since the connections for various types greatly vary in details, so that a blueprint must be supplied

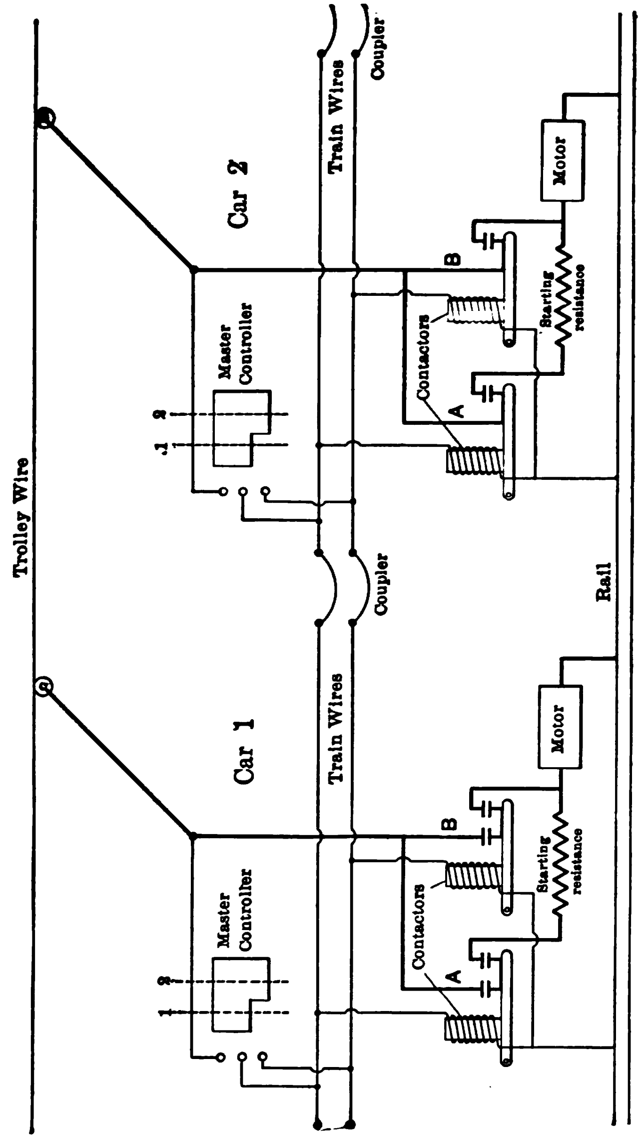


FIG. 512. Diagram illustrating the principle of the multiple-unit control of trains.

with each controller. A diagram of the general disposition of parts in a car is shown in Fig. 513 and is explained in the next article. With a clear understanding of this diagram and of the principle illustrated

in Fig. 509, the student should find no difficulty in tracing out the actual connections on a given controller.

In the Westinghouse electro-pneumatic controller the contactors, such as A and B (Fig. 512), are actuated by compressed-air cylinders. The auxiliary or the control circuit may be supposed to be fed from a small storage battery. Energizing one or the other of the train wires admits compressed air into the corresponding contactor cylinders, operating the pistons. The admission valves are electrically controlled.

709. Disposition of Parts of a Multiple-Unit Controller in a Car. — The general arrangement of the parts of an electrically operated controller is shown in Fig. 513. The power circuit is again shown by heavy lines, the control circuit by light lines; several wires of either circuit, running together, are combined in a cable. All the contactors of the car are placed in a box, which is connected to the source of power, and to the motors, through the reversing switch (reverser). The motor rheostats are also connected to the corresponding contactors. In this way any desired connections are established between the trolley, the motors, and the rheostats. The reverser, which is also electrically operated, determines the direction of motion of the car.

The auxiliary circuit comprises (a) the train-control cable, running through the whole train, and (b) the car-control cable through which the contactors of a particular car are energized. When the master controller on the front car is set in a certain position, definite wires of the train-control cable are energized, and they energize, through the "connection boxes," the corresponding wires of the car-control cables on all the cars. The latter wires operate certain contactors, and thus establish the required connections in the power circuit.

Each car is provided with two master controllers, as it may be desired to operate it from either end. A cut-out switch and fuses are provided on each car-control cable, in order to be able to disconnect a disabled equipment. The control rheostat, shown in the diagram, contains resistances in series with the windings of the contactor solenoids; these resistances reduce the control currents to the required value.

710. Details of Operation. — The most noteworthy feature of the multiple-unit controller is *automatic acceleration*. The motorman may throw his handle in the "full parallel" position, corresponding to the maximum speed, from the very start: with an ordinary drum controller this would either open the circuit-breaker or produce a most undesirable jerk of the car. But the unit switches, or contactors, are electrically interlocked, so that they can pick up in a certain succession only. Moreover, as soon as the line current exceeds a certain limit, the current-

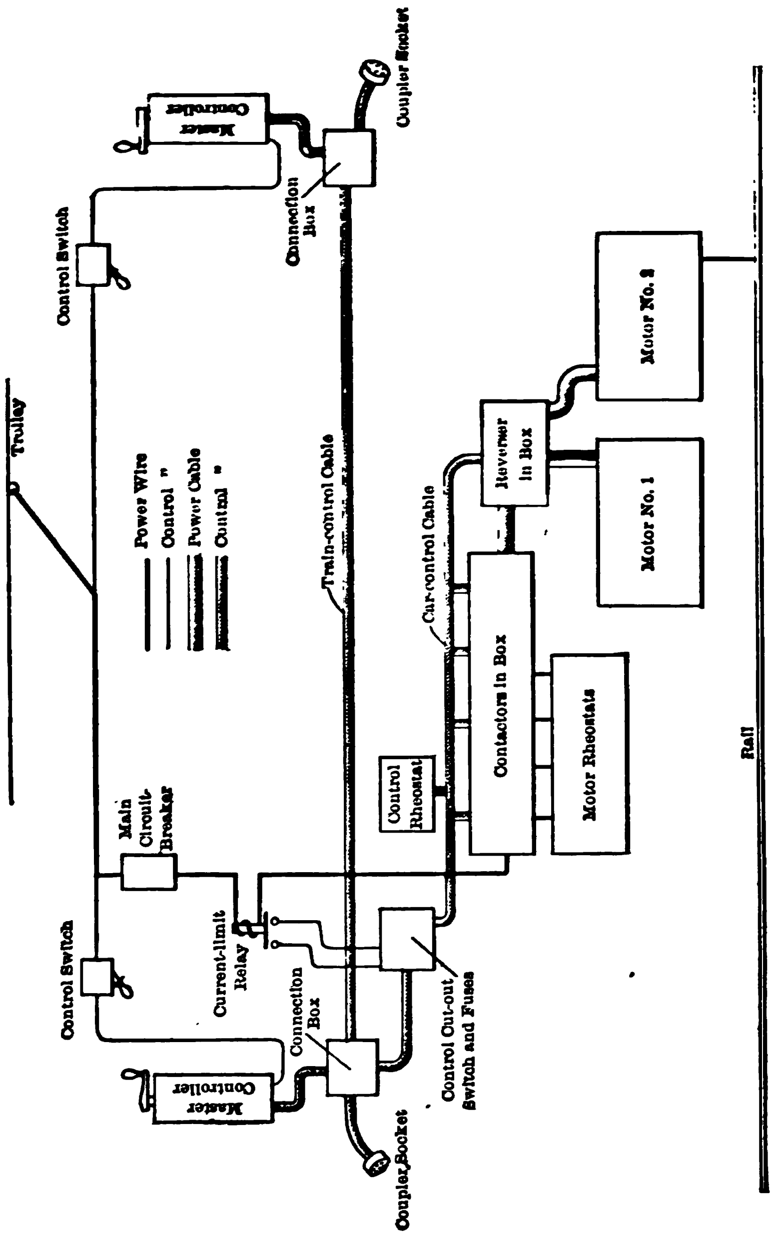


FIG. 513. Diagram of a car equipped with a multiple-unit controller.

limit relay, shown in Fig. 513, prevents any further change or connections, at the same time holding up the contactors already closed.

The master controller has two handles, one for speed control, the other for reversing the motors; in this respect it is similar to the hand-operated controller, shown in Fig. 502. As the gradual cutting out of resistances is done automatically by the contactors themselves, there are but four positions of the regulating handle:

(1) Motors in series, with all resistance "in."
(2) Full series.
(3) Motors in parallel, with all resistance "in."
(4) Full parallel.

The interlocking of the handles is the same as explained in § 700.

In the first position of the handle, one of the control wires leading into the reverser box is energized, and the reverser is thrown into the "forward," or the "reverse" position, according to the position of the reversing handle of the master controller. In this movement the reverser closes an auxiliary contact which completes the circuit of the coil of the so-called "series" contactor. The contactor is energized and closes the motor circuit with all the starting resistances in series. The train starts, but no more contactors are brought into play, as long as the master controller is on the first notch.

By moving the handle into the second position, the motorman closes the circuit of the so-called "accelerating" wire, which energizes a *second* contactor; this contactor short-circuits part of the resistance in series with the motors. At the same time, this second contactor closes the circuit of the solenoid of a *third* contactor, which short-circuits some more resistance in the motor circuit. This process goes on, until all the resistance is short-circuited, and the motors are in full series.

The speed at which the successive contactors are lifted up, is controlled by the above-described current-limit relay. When the first contactor in the second position of the handle is closed, it automatically shifts the circuit of its own solenoid to that of the preceding solenoid, making it thus independent of the "accelerating" wire. If the main current is too heavy, the accelerating circuit is opened by the current-limit relay, preventing the next contactor from being energized. This does not open, however, the contactor already in the circuit, because its solenoid is now connected around the accelerating wire. As soon as the current drops to its normal value, the current-limit device again closes the circuit of the accelerating wire, which energizes the next solenoid, etc. The plunger of the relay has some lost motion, so that it does not open the accelerating circuit, before the solenoid has been transferred to the other circuit.

In the third position of the operating handle of the master controller, additional control wires are energized, other contactors are brought into action, and the connections of the motors are changed from series to parallel. Bridge connections are used (§ 698) with this type of multiple-unit controller. In the fourth position of the motorman's handle, operations are performed similar to those in the second position, but with the motors in parallel.

It is clear, then, that the controller handle may be moved into the fourth position from the very start, because the contactors can be energized in a certain order only, and the rate at which the successive contacts are closed is controlled automatically by the current-limit relay.

711. EXPERIMENT 34-B. — Operating a Multiple-Unit Controller. — The purpose of the experiment is to give practice with the circuits, construction and operation of this system of control. The principles explained in the preceding articles apply to an electric as well as to an electro-pneumatic controller. An exact diagram of connections always accompanies a controller. It is out of the question to have all the wiring done during one or two laboratory periods, but the most important connections should be made by the student himself, in order to become familiar with the wiring of the controller.

Connect the controller to two railway motors and operate it under the conditions under which it is operated in practice. Observe the action of the interlocking and safety devices. If possible, put a certain load on the motors, and also have them belted to a fly-wheel to imitate the inertia of the car. Measure the total time of operation of the contactors, also approximately the moments at which the new contactors operate. Note the corresponding fluctuations of the current. Vary the load, the inertia, the setting of the current-limit relay, and observe the difference in the operation of the controller. Make sketches of the contactors, of the reverser, the relay and the master controller.

Report the actual connections, or at least the details by which they differ from those described above. Draw rough sketches showing the construction of the most important parts of the controller. Give the results showing the time of starting, fluctuations of current, effect of various settings of the current-limit relay, etc.

3. ACCELERATION AND RETARDATION TESTS ON CARS.

712. Car schedules on long suburban and interurban lines depend essentially upon the maximum speed which the motors can develop in a given car and with the profile of the road. On the contrary, car schedules within city limits depend to a considerable extent on the

rate of *acceleration* and deceleration (retardation) possible with a given equipment. Stops within city limits are so frequent that generally a larger part of the time is taken by accelerating and stopping the car, than in running it at a uniform speed.

A study of car acceleration and deceleration is thus important for determining the schedules and the power consumption to be expected with a given equipment. Experiments on actual cars are performed from time to time by operating and manufacturing companies, and the results are used as a basis for designing new equipments. Numerous tests of this kind were performed in 1904 under the supervision of Profs. Norris and Swenson, acting for the Electric Railway Test Commission of the Louisiana Purchase Exposition. The very interesting results of these tests may be found in the printed report of the commission.

In order to observe the performance of an actual car, with the action of its inertia, friction, air resistance, influence of grades and track curvature, etc., a long experimental track and a specially equipped car must be available. All that can be attempted along these lines, in the laboratory, is an approximation on a small scale to actual conditions; and a demonstration of instruments, used in actual car tests for recording amperes, speed, distance, etc. At the same time it is believed, that some acquaintance with the methods and devices used in acceleration and retardation tests, as well as some practice in working out the results, constitute a good preparation for the performance of similar experiments on a larger scale. Moreover, even such a laboratory experiment helps one to understand the most important factors affecting the practical operation of electric cars.

713. Description of Apparatus. — A simple laboratory arrangement for acceleration and retardation tests, which may be built at a moderate cost and which well serves the purpose, is shown in Fig. 514. It consists of a small series motor, belted to a shaft which carries one or more heavy fly-wheels and a pulley provided with a Prony brake. The motor represents the motor equipment of a street-car; the fly-wheels play the part of the car inertia; the Prony brake load supplies the frictional, grade and other resistances of the car. The set can be run under various electrical and mechanical conditions, and the results observed may be applied, at least qualitatively, to actual cars.

Speed and current vary so rapidly during the period of acceleration, that it is hardly possible to take sufficiently accurate readings with an ordinary tachometer and an ammeter. Therefore, recording instruments must be provided, similar to those used in testing actual cars. In the apparatus shown in Fig. 514 a roll of paper is driven at a uniform

speed by a chronograph. The pencil A traces amperes, the pencil T marks seconds of time, and the pencil D marks distances run by the car. These three pencils are actuated as follows:

The pencil A is connected to a cord fastened at the other end to a handle h mounted on the ammeter. This ammeter is connected into the motor circuit and indicates amperes input into the motor. An observer follows with the handle h the indications of the ammeter pointer as closely as possible, and in this way transmits them to the pencil A. The pencil T is operated by the electromagnet t whose circuit is closed once a second by the pendulum S. The pencil D is

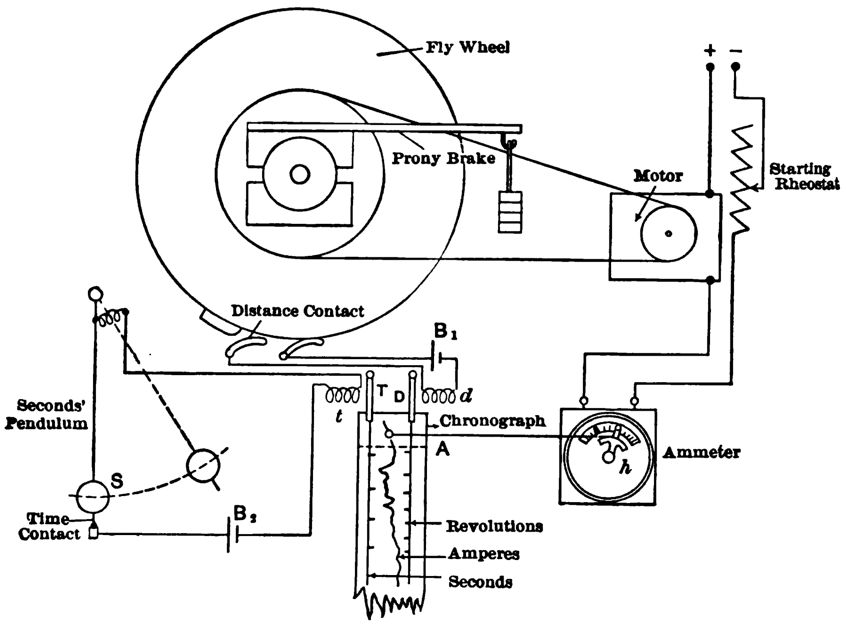


FIG. 514. A laboratory apparatus for study of acceleration of electric cars.

actuated by the electromagnet d, whose circuit is closed once during each revolution of the fly-wheel shaft. With this arrangement, amperes are plotted directly to time as abscissæ, while from the marks made by the pencils T and D the time-distance curve or the speed curve of the car can be easily constructed.*

714. Car Performance Curves. — Car performance curves, in their elementary aspect, are represented in Fig. 515. In the most general case they consist of four parts: (1) acceleration period, (2) running

* For some other special instruments of this kind see Chapter III in Ashe and Keiley's *Electric Railways*, — Train Recording and Indicating Instruments.

at full speed, (3) coasting, and (4) braking. The toothed part of the current curve corresponds to the first part of the acceleration period, when the controller resistances are gradually cut out. With a two- or four-motor equipment this part consists of two distinct portions — motors in series and motors in parallel. The smooth part of the current curve during the period of acceleration corresponds to the increase in speed at full voltage. During the second period (full speed) the current is constant, if the profile of the road is uniform; then the current is cut off, the car is allowed to coast for a reasonable length of time, and finally the brakes are applied in order to stop it at the right place.

The distance covered by the car (counting from the preceding stop),

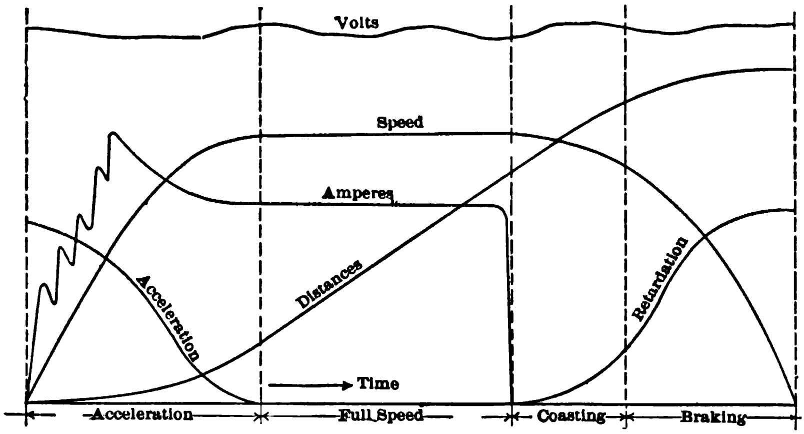


FIG. 515. Car performance curves.

increases at first slowly, then faster, and when the car reaches its final speed the distance increases proportionally to the time. During the periods of retardation the distance again increases more slowly. The speed curve reaches its maximum in the middle portion and gradually decreases to zero at both ends. The ordinates of this curve are proportional to the tangents of the distance-time curve ($v = ds/dt$).

Acceleration is positive during the first part of the run, and negative during the last two periods. When the car is running at full speed the acceleration is $= 0$. The ordinates of the acceleration curve are proportional to the tangents of the speed curve (accel. $= dv/dt$).

715. EXPERIMENT 34-C. — Acceleration and Retardation Tests on an Electric Car. — The experiment consists in getting data for the four parts of the above performance curves (Fig. 515). These parts are then put together to form complete performance curves,

from which certain deductions may be drawn in regard to the equipment and the possible schedule.

(1) Begin the test by calibrating the Prony brake for different speeds; in other words, determine the values of torque which must be applied to the pulley in order that the motor may reach certain final speeds. Then begin taking data for the first part of the performance curves (acceleration). Use recording instruments, such, for instance, as are shown in Fig. 514, and take several runs, varying the following factors:

(*a*) The period of time during which the starting resistance is gradually cut out. Move the rheostat handle as evenly as possible. The more slowly the resistance is cut out, the more time it takes to reach the final speed, but the less is the rush of current; the subsequent heating of the motor and the waste of power are thus reduced.

(*b*) The final speed attained by the motor: this is done by properly setting the Prony brake according to the calibration, as mentioned before.

(*c*) The pulley ratio on the motor shaft and the fly-wheel shaft: in application to actual cars this means changing the gear ratio between the motor and the axle. The lower the ratio (the nearer to each other the diameters of the gears), the higher the speed of the car, and the heavier is the duty required of the motor.

(2) The second part of the curves (running at full speed) does not require any extra test, since the necessary data can be obtained from the previous runs by continuing them until the speed and the amperes input become constant.

(3) The necessary data for the third part of the curves (coasting) are obtained by bringing the fly-wheel to the highest safe speed and then observing the gradual decrease in speed due to the frictional resistance. This experiment should be performed with the same values of brake load as were used in determining the preceding curves. Instead of recording the speed with a chronograph, it is preferable in this case to use a tachometer, or else to use the motor itself as an electrical tachometer. After the set has been brought up to the desired speed, the current is cut off, and the motor field excited with a small current from an independent source. The voltages thus induced are proportional to the instantaneous values of speed, and may be read on a suitable voltmeter.

(4) The last part of the curves (braking) are taken in a similar way. The brake can be applied to the fly-wheel; or else the Prony-brake load can be increased to give the necessary braking effect. Repeat this run with a few different values of brake pressure, in order to see the effect of this factor on car schedule.

It is also desired that the student try to stop the fly-wheel by converting the motor into a generator and closing it on suitable resistances (starting resistance can be used for this purpose). See that the armature leads are reversed in the brake position, so as to have the right direction of residual magnetism in the field. At first, the motor must be closed on a comparatively high resistance, in order not to overload it. As the speed decreases, the resistance is gradually cut out of the circuit, and finally the motor can be short-circuited on itself. Have an ammeter and a voltmeter in the circuit, so as to observe the electrical relations. Take ampere-time and speed-time curves with various rates of cutting out the resistance; or else, take curves for different values of "braking current," regulating the resistance so as to keep the current in each case as nearly constant as possible.

Report. The results of the experiment should be applied for determining some of the schedules which the equipment under test can give in commercial service. Assume a certain distance between the stops, and plot the curves shown in Fig. 515, selecting such experimental data as to have this distance covered in minimum time. This means cutting out starting resistances as fast as possible, and applying the maximum braking pressure immediately after the power has been shut off; in other words, running as long as possible at maximum speed and leaving out the coasting period. Assume a certain length of stops, say 5 seconds or thereabouts, and take the ideal and the simplest case that the car performs a regular schedule of the above runs and stops all day. Figure out the average commercial speed with and without stops, kw.-hrs. power expenditure per unit distance covered by the car, and the average effective current (square root of the mean of the squares of current). This latter should not be larger than the rated current of the motor; otherwise the temperature of the motor will rise beyond the safe limit, after a few hours run.

Should it result, that the above acceleration and speed overload the motor, the schedule should be modified so as to reduce the power input, of course at a sacrifice of the average speed or of the number of trips per day. Take a lower rate of acceleration, introduce a reasonable amount of coasting and reduce the brake pressure. Make these changes by trials until a satisfactory schedule is arranged, with as high an average speed as possible.

As another alternative for bringing the schedule within the capacity of the motor, the gear ratio can be reduced, so as to decrease the maximum speed. Compare the schedule and the power consumption attained in this way with those obtained with the motor geared for a higher speed (with the same average commercial speed).

Numerous performance curves taken from experiments on actual cars may be found in the above-mentioned *Report of the Electric Railway Test Commission.*

4. AIR-BRAKES.

716. One of the most important items in the equipment of a car is the brake. Most of the electric cars in common use are equipped with *hand-brakes*, in which the brake shoes are forced against the wheels by a system of levers operated by a handle under the control of the motorman. The general tendency towards an increase in the weight and size of cars has caused hand-brakes in many cases to be inadequate for control. This has resulted in the introduction of *air-brakes*, in which the shoes are pressed against the wheels by means of a piston operated by compressed air.

Compressed air may be supplied either by a compressor on the car itself, or the car carries an air-storage reservoir which is replenished at certain intervals from station tanks. The car compressor may be driven either by a separate electric motor, or directly from a car axle. A separate motor compressor on each car is the best solution, if the road can afford to so equip the cars.

717. Straight-Air Brake Equipment. — The general arrangement of parts of a simple air-brake equipment, as used on single electric cars (not on trains), is shown in Fig. 516. The principal parts, clearly seen in the figure, are: The motor-compressor, the compressed-air reservoir, the brake cylinder, and the operating (or motorman's) valves, one on each end of the car. To apply the brakes, the motorman turns the handle to such a position, that compressed air from the reservoir flows into the brake cylinder. This causes the piston inside of the cylinder to move and set the brakes. To release the brakes, the operating handle is moved to such a position that the air reservoir is cut off from the brake cylinder, and the latter is connected to the atmosphere (through a muffler, in order to deafen the disagreeable noise of the escaping air). As the air pressure in the cylinder is reduced, the piston travels back under the influence of an opposing spring inside of the cylinder.

The motorman's valve has four positions: The extreme left position of the handle is the "release" position, in which the brake cylinder is connected to the atmosphere, and the air reservoir is closed. The next position is the "running" or the "lap" position; here all the ports are closed, so that if there was any air in the brake cylinder it remains there, as long as the handle is in the "lap" position. The next position corresponds to the so-called "service application" of the brakes; the brake cylinder is disconnected from the atmosphere and is put in

communication with the compressed-air reservoir, through a small opening. The air flows to the brake cylinder, and the brake shoes are gradually applied to the car wheels. When the car has sufficiently slowed down, the handle is returned to the lap position, in order not

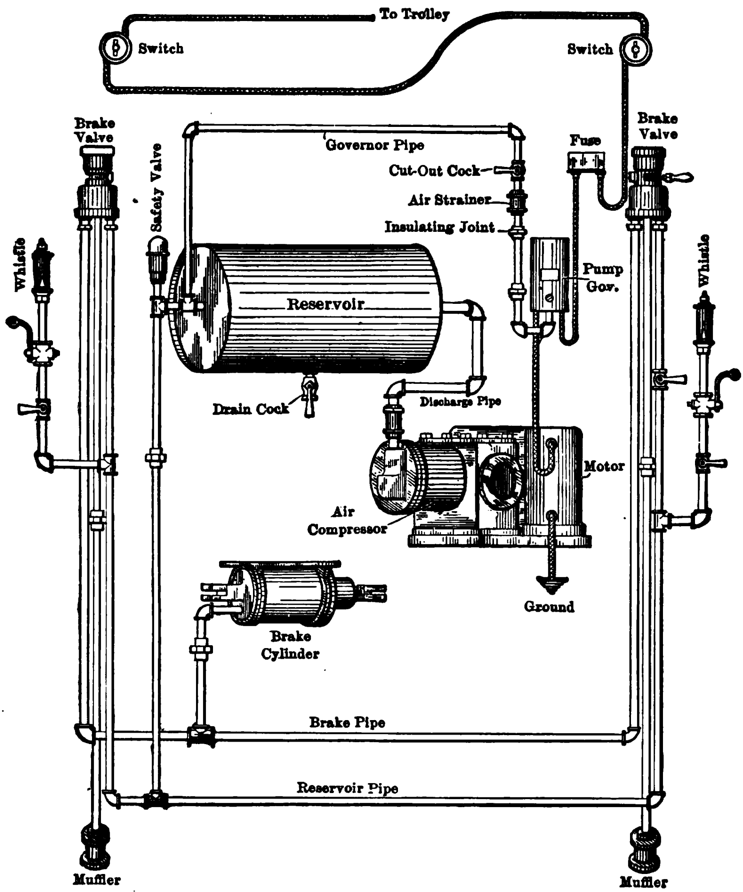


FIG. 516. Westinghouse straight-air brake equipment.

to increase the pressure further. The extreme right position of the operating handle gives an "emergency application" of the brakes; the air reservoir is connected to the brake cylinder through a large port, so that the full air pressure is instantaneously applied to the wheels.

This gives a very unpleasant sudden stop, and should be used in extreme cases only, for instance, in order to avoid a collision, to save a life, etc.

The electrical connections in such an air-brake equipment are very simple: The current from the trolley passes through two snap-switches, one on each platform, through a fuse block and the pump governor to the motor. The motor is series-wound and has no starting resistance whatever; the current passes through its armature and field, and thence to the ground with the rest of the car current.

The pump governor, shown in the diagram, automatically starts and stops the compressor-motor, and in this way maintains the air pressure in the reservoir within the required limits. The governor consists of a snap-switch, actuated by the piston of a small air cylinder, connected to the air reservoir. When the pressure has reached its upper limit the piston moves against a spring and opens the electric circuit, stopping the motor. When the air pressure reaches its lower limit the spring returns the piston to its former position, and closes the circuit; the motor starts again and raises the air pressure.

The other parts of the equipment are: A safety valve, limiting the pressure in the main reservoir to a predetermined value; and a duplex pressure gauge (with two hands) on each platform; one hand shows the pressure in the reservoir, the other, in the train pipe. The signal whistles, used on inter-urban cars, are operated by the air from the same main reservoir as the brakes.

718. EXPERIMENT 34-D. — Operating Straight-Air Brakes. — An equipment should be provided for this experiment, similar to that shown in Fig. 516, and conveniently arranged so that all the parts are accessible for study. Before beginning the experiment, carefully study the piping and the electrical connections of the outfit. Then the compressor set must be started and the pressure in the main reservoir brought up to the required value. This will make the equipment ready for operation. The work should be conducted as follows:

(1) Practice operating the motorman's valve so that you know exactly all the positions and what operations they represent; also observe the variations in pressure, without taking any exact readings.

(2) Make a study of operating conditions of the motor-compressor and of the main reservoir. Assume a certain schedule which the car is supposed to perform; say, a stop every n minutes, requiring an application of the brakes, and a certain number of seconds x that the brakes must be "on." Actually perform this schedule during 15 or 20 minutes, and observe as accurately as possible the following: per cents

time during which the compressor is operating, and at rest; amperes and volts that it takes to operate the motor; variations of pressure in the main reservoir; the pressure at which the governor starts the motor and at which it opens the circuit. Plot the results to time as abscissæ.

(3) Take pressure-time curves showing how the pressure changes in the different parts of the equipment when the motorman's valve is moved in a certain position, or a complete cycle of handle operations is performed. Read the gauges, always beginning with the same pressure in the main reservoir. Plot the pressures to seconds time as abscissæ, also mark the time of the beginning and the end of the travel of the brake-cylinder piston.

(4) Measure with a spring balance the brake-shoe pressure at different air pressures in the brake cylinder. Check the results with the theoretical pressures figured from the piston area and the leverage ratio.

719. Automatic Air-Brake Equipment. — The above-described air-brake equipment, so-called *straight-air system*, is no longer used on steam railroads, notwithstanding its simplicity; even on electric roads it is in some cases being replaced by the more complicated *automatic air-brake equipment.* A drawback of the straight-air system is that with a train, consisting of several cars, an appreciable time elapses before the air pressure is transmitted along the train pipe. Therefore, the brakes on the front cars are set earlier than on rear ones, and the latter have a tendency to run into the front cars. Another important drawback of the straight-air system is, that should there be a leak in the train pipe, or should the train be pulled asunder, the brakes can no longer be applied; this might lead to a serious accident.

These disadvantages are eliminated in the automatic air-brake system, with which the brakes on all cars, even with the longest freight trains, are set practically simultaneously. Moreover, should there occur a break in the train pipe, or a serious leak, the brakes are applied *automatically*, and the train stopped.

These advantages are obtained by the addition of an auxiliary air reservoir on each car (Fig. 517). Compressed air for brake application has to flow but a short way between this auxiliary reservoir and the brake cylinder on the same car; this insures a simultaneous application of the brakes on all the cars. The auxiliary reservoirs are recharged from the main reservoir during periods of release. Each auxiliary reservoir is operated by a so-called *triple valve*, placed on each car near the brake cylinder. This valve automatically performs the motorman's duties for each car; it sets the brakes, releases the brakes, and recharges the auxiliary reservoir. *The triple valve assumes one of these three positions* (hence the name *triple* valve) *according to the pressure in the*

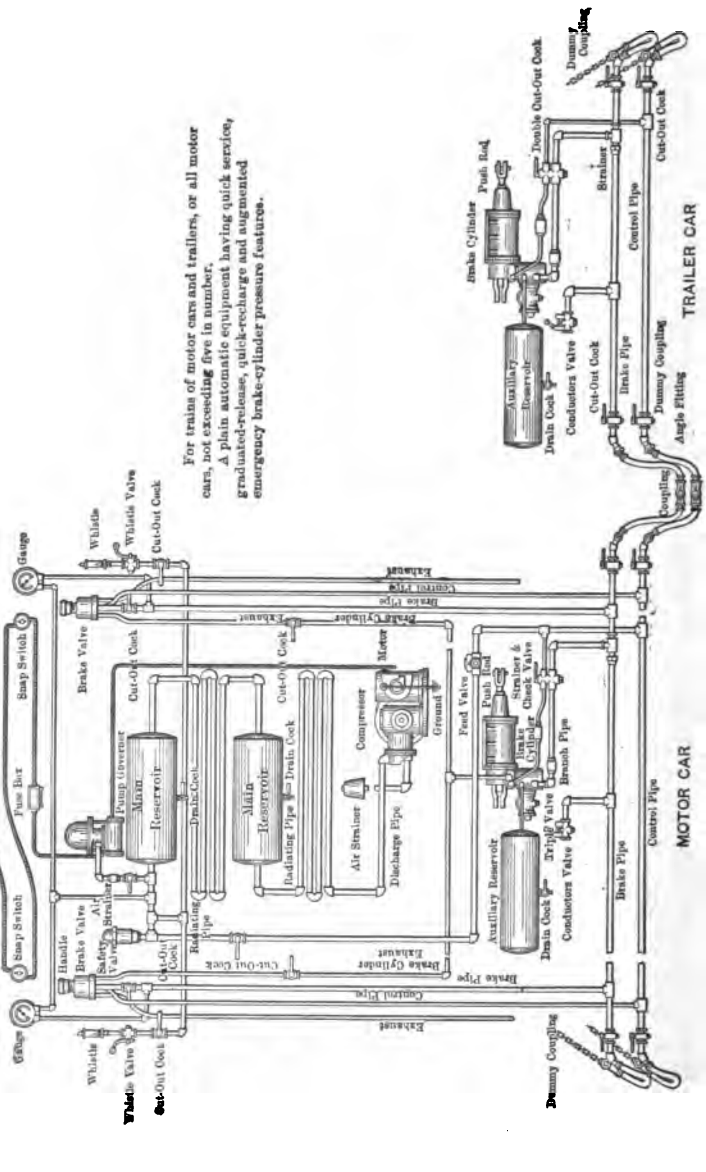


FIG. 517. Westinghouse automatic air-brake equipment.

train pipe. The motorman on the front car has only to establish a certain pressure in the train pipe; the triple valves on all the cars operate accordingly.

The triple valve is so constructed that increasing the pressure in the train pipe releases the brakes, while with the straight-air brake system this would set the brakes. With an increased pressure the triple valve is moved to such a position that it connects the brake cylinder to the atmosphere. Reducing the pressure in the train pipe gives a preponderance of pressure to the auxiliary reservoir. The air in the latter shifts the valve out of the way, puts itself into communication with the brake cylinder, and sets the brakes. For further details of the operation of the triple valve, see § 721 below.

720. Motorman's Valve. — With the automatic-air system there are five different positions of the motorman's operating valve: release, running, lap, service application and emergency application. As the motorman faces the valve, the position farthest to his left is the release; the other positions follow to the right in the order named.

The purpose of the release position is to provide a large and direct passage from the main reservoir to the train pipe, in order to insure a quick release and recharging of the auxiliary reservoirs. With the valve in this position, a "warning port" discharges air from the main reservoir into the atmosphere with a considerable noise, attracting the motorman's attention, if he neglects to move the valve handle to the running position. This is necessary, because the pressure in the main reservoir must be higher than in the main pipe; it is about 90 pounds in the former and only 70 pounds in the latter.

In the running position of the valve, the main reservoir is connected to the train pipe through a special feed valve, placed under the motorman's operating handle. This valve lets the air pass into the train pipe when the pressure in this pipe is below 70 pounds, and thus supplies the leaks.

In the lap position all the ports are closed and thus made inoperative. This position is used after the service application of the brakes, in order to keep the brakes set in the desired position, preventing an interchange of compressed air.

In the service-application position, the train pipe is connected to the atmosphere through a small port; the reduction of air pressure effects the movement of the triple valves to the right, and the brakes are set.

The emergency position is distinguished from the preceding one by offering a much larger passage to the air into the atmosphere; this causes a nearly instantaneous application of the brakes throughout the train.

Some motorman's valves are provided with two service positions: one for slow application, for instance to prevent acceleration on grades, the other for quick service application, such as would be used for rapid stops with fast city schedule.

721. Triple Valve. — The action of the triple valve may be understood from its cross-section shown in Fig. 518. The valve shown there is the simple and original form of the device, which has now been superseded by the so-called quick-action triple valve. The quick-action feature will be mentioned later on.

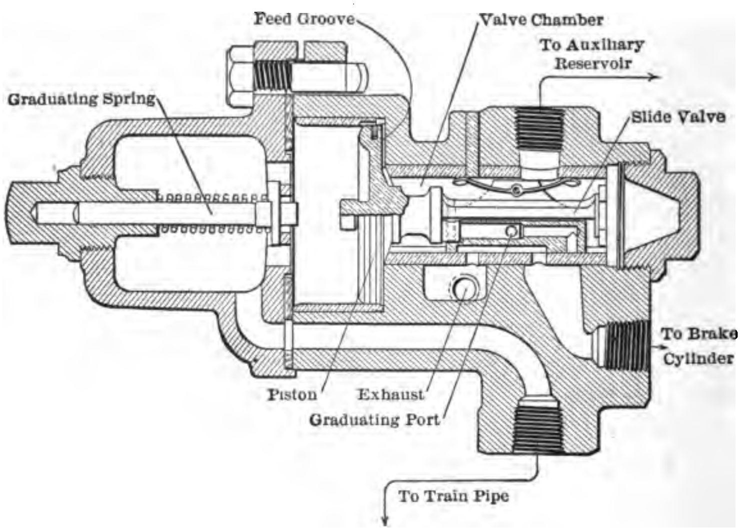


FIG. 518. Westinghouse triple valve.

The triple valve is connected to the auxiliary reservoir and to the brake cylinder on one side, and to the train pipe on the other side (see Fig. 517); it has also an opening to the atmosphere (exhaust). The necessary connections are accomplished by the slide valve, which is operated by the piston to its left. This piston is in turn actuated by the difference in pressure in the auxiliary reservoir and in the train pipe.

When air is admitted to the train pipe, through the motorman's brake valve, the piston is forced to the right-hand end of its stroke. In this position the feed groove is uncovered, and the air is permitted to flow past the piston into the auxiliary reservoir. The feed groove is made of such a size that about sixty seconds are required to fully charge an empty auxiliary reservoir. In this position of the piston, the

brake cylinder is connected to the atmosphere through the cavity in the slide valve, the brakes being thus released. It should be noted, that only in this position can the auxiliary reservoir be recharged.

Now, if the train-pipe pressure be reduced four or five pounds, the preponderance of pressure on the auxiliary reservoir side of the piston will cause it to move to the left until it strikes the flexible abutment. In this position, known as *service application*, a graduating port in the slide opens a small passage from the valve chamber to the brake cylinder port: The air from the auxiliary reservoir then flows into the brake cylinder, until the air pressure in the auxiliary reservoir is reduced slightly below that in the train pipe. As there is a small amount of lost motion between the piston stem and the slide valve, the slight excess of pressure now on the train-pipe side, moves the piston inwardly far enough to close the graduating port, but has not sufficient power to overcome the friction of the main slide valve. The triple valve is now in the *lap position*, with all communications cut off between the train pipe, auxiliary reservoir, brake cylinder and the atmosphere.

This cycle of operations may be repeated with a resultant increase of the brake-cylinder pressure and a decrease of the auxiliary reservoir pressure, until their point of equalization is reached; after this any further reduction of the train-pipe pressure is not only useless but wasteful.

On the other hand, a sudden reduction of the pressure in the train pipe causes the piston to move to the left with such force, that it compresses the graduating spring and uncovers the brake-cylinder port. This opens a direct passage between the auxiliary reservoir and the brake cylinder, giving an almost instantaneous application of the brakes, necessary in emergencies.

Experience has demonstrated, that the above-described triple valve does not act quickly enough on long trains, giving the same trouble, as had been experienced with the straight-air brake system, namely, the rear cars running into the front ones. This fault has been remedied by the introduction of the so-called *quick-action triple valve*, in which a direct passage is provided between the train pipe and the brake cylinder. This passage is usually closed by a valve, but is opened in the emergency position of the slide valve by an ingenious mechanical combination. The opening of this passage accomplishes two results: (1) Venting of air from the train pipe helps to reduce pressure in it, and so assists the action of the brake on the next cars. (2) A pressure of 60 pounds is obtained in the brake cylinders, instead of 50 pounds, obtainable from the auxiliary reservoirs.

It is claimed that in a 50-car train but three seconds elapse between the movement of the engineer's valve and the application of the brakes on the last car, when the above quick-action attachment is used.*

722. EXPERIMENT 34-E. — Operating Automatic Air-Brakes. — The principal parts of the equipment are described in the three preceding articles. The minor parts may be easily understood from the diagram shown in Fig. 517. In performing this experiment, it is well to have a dummy motorman's valve and a dummy triple valve, showing a cross-section of these devices. The dummy valves should be connected mechanically to the actual valves so as to follow their movements. This enables the student to see clearly the relative positions of the various slides and ports. For further instructions, see § 718.

(*) For more recent improvements in triple valves, namely, the graduated-release and the quick-recharge features, see a paper by Mr. C. C. Farmer in the *Proceedings of the Air-Brake Association*, 1906, p. 126.

CHAPTER XXXV.

ELECTRIC HEATING AND WELDING.

I. ELECTRIC HEATING.

723. AMONG minor applications of electricity, heating and cooking by electric current are growing continuously in importance. It seems necessary, therefore, to become familiar with the operation of electric heating devices, and with the numerical relations governing transformation of electrical energy into heat. It may be stated at the outset that, from the standpoint of pure heat economy, it is ordinarily cheaper to heat a room or cook with gas or coal, than by electric current: In the latter case the thermal energy of coal or gas must first be communicated to the steam-boiler, then be converted into mechanical and electrical energy in the power house, transmitted through a line, and finally converted into heat again, instead of being directly used in a stove. However, gas light is also cheaper than electric light, and yet lighting by gas is gradually giving place to electric lighting. Here, as in the case of electric heating devices, *indirect advantages*, and *convenience, or comfort* gained, overwhelm the mere difference in price, and make the application of electric current for heating desirable and rational. Moreover, in places where cheap water power is abundant, and coal is scarce, heating and cooking by electricity are cheaper than by coal or gas.

724. Principal Heating Devices. — The principal forms of electric heating and cooking devices, now in use, are as follows:

(1) Street-car heaters, and radiators for heating rooms.

(2) Kitchen utensils: food, water, coffee and tea heaters and boilers, chafing dishes, cook stoves, etc.

(3) Soldering irons, laundry-, factory-, tailors'-irons, etc.

(4) Curling-iron heaters, cigar lighters, heating pads, etc.

An electric kettle is shown in Fig. 519; it has a double bottom accommodating a resistance, in which heat is produced. This particular device has three terminals, making it possible to have either the whole winding or part of it connected in the circuit. This gives three values of heating: intense heat, medium heat, and low heat.

Fig. 520 shows an electric soldering iron; its construction is clear from the sketch. An electric flatiron is represented in Fig. 521; it can be

connected to an ordinary lamp socket, and heats very quickly after the current is turned on.

All these devices, however different in form and application, are based on the familiar Joule's law, that the rate of generation of heat, developed by the passage of a current through a conductor, is equal to $I^2 R$ watts, where I is the current in amperes, and R the resistance of the conductor in ohms. Any amount of heat can thus be generated by electric current, by suitably selecting I and R, provided the conductor and the vessel can withstand the temperatures resulting.

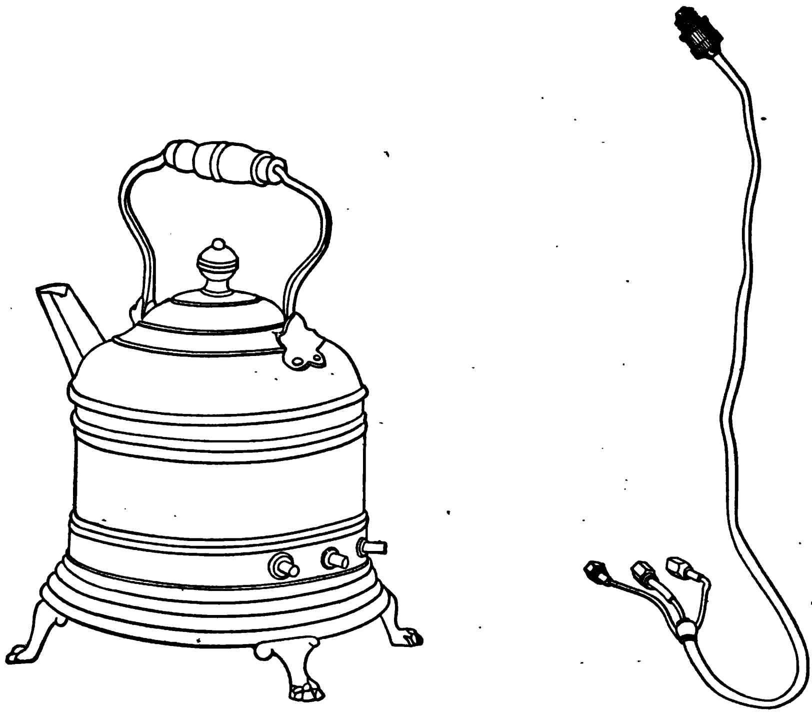


FIG. 519. Electric kettle.

The introduction of electric heating and cooking devices is very desirable for electric operating companies, since it gives them some day-load, especially in residence districts. In the business part of cities, day-load is supplied by motors in industrial establishments, by elevators, fan motors, etc., while in residence districts practically all of the demand comes during the evening, and the machines in power houses, necessarily large enough to carry the evening peak of the load, are running uneconomically during the day, at a very light load. The

day-load can be increased by stimulating the use of electric heating devices. In other words, electric cooking and heating devices tend to improve the *"load factor"* of the power houses, or the ratio between the average and the maximum load of a station; this ratio plays an important part in the economic operation of central stations.

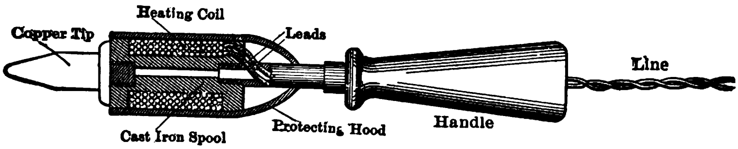


FIG. 520. Electric soldering iron.

725. Forms of Heating Elements. — Materials possessing high specific resistance are used for heating elements, in order to generate large amounts of heat within comparatively small space. Such elements consist either of wire or of metal strips, and may be entirely surrounded by air, insulated with mica, or embedded in special enamel. An original type of heating element, shown in Fig. 522, consists of a strip of mica covered with a thin layer of non-oxidizable metal, which is firmly secured to the mica by a process of firing. The conducting strip is covered by another piece of mica, and the whole is inclosed in a pro-

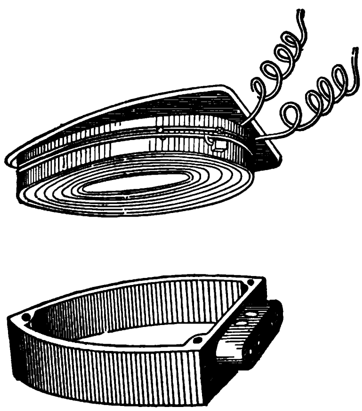


FIG. 521. Electric flatiron.

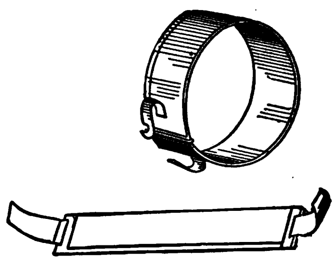


FIG. 522. Prometheus heating element.

tecting metal case. Such elements are placed inside of utensils nearest to the place where heat is required.

726. Conversion of Watts into Heat Units. — In testing electric heating utensils one has to know numerical relations between watts input, and the output expressed in heat units. Confusion sometimes arises in the conversion, because the electrical unit "watt" refers to

one second of time, while the heat units do not imply time. Correct results are obtained by using either "watt-seconds" (joules) or "thermal units per second."

The fundamental numerical relation is as follows: *When one kilowatt, or* 1000 *watts, of electrical energy are continually absorbed in a resistance, an amount of heat is liberated, equal to* 0.948 *British thermal units* (*B. T. U.*) *per second, or* 240 *gram-calories per second.* Remembering, in addition, that one horse-power is equal to 0.746 kw., we have all the necessary data for a theoretical conversion of electrical energy into heat, or mechanical power. The relations are somewhat more complicated in practice because of the losses which occur in the transformation of one form of energy into another.

727. EXPERIMENT 35-A.—Testing Electrical Cooking Utensils.—A water heater and a cook stove may be selected as representative of this class of devices. In the water heater, heat is communicated to the water directly, while in the cook stove it must be first communicated to the vessel containing the water. The experiment consists in determining the relative and absolute efficiencies of the devices.

(*a*) Measure the total electrical input necessary for bringing a known quantity of water to the boiling-point; the useful output is equal to the number of heat units required for bringing the water to the boiling-point. The ratio of output to input (both reduced to the same units) represents the efficiency of the device. During the process of heating, read temperature rise several times per minute, also the approximate temperature of the outside walls of the heater, and the distribution of heat by means of a suitable pyrometer, or an electric thermometer.

(*b*) It is interesting to investigate the influence of the supply voltage on the efficiency and power consumption of the devices; also on the amount of time that it takes to bring the same quantity of water to the boiling-point. This time depends essentially on the initial temperature of the water and of the vessel itself: In order to get comparable results, be sure to start all the runs under the same conditions.*

(*c*) Another question to be investigated is the comparative cost of cooking by gas and by electricity. An ordinary gas stove and a gas meter should be provided for this purpose; the same quantity of water, as was used in the electric heater, is brought to the boiling-point by using a gas heater, and the number of cubic feet of gas consumed is

* Great care should be exercised in handling electric cooking devices: the boiler must be filled with water, before the current is put on. Otherwise, it is easy to burn out the heating resistance. Current must be turned off as soon as a run is completed.

determined by the meter readings. The price of gas in different localities varies from $0.80 to $1.50 per 1000 cu. ft.; the price for electric current is between 8 and 15 cents per kilowatt-hour. On the basis of these figures a comparison of cost can be readily made. As was stated above, however, the difference in price alone does not decide the relative advantages of using gas or electric current.

There is one test which in spite of its great practical importance must be omitted in the laboratory: This is the "life test," or the determination of the number of hours of service which a heating device can stand before its heating element is burned out. For obvious reasons such a test could not be performed in a student's laboratory.

Report. Plot curves of temperature rise and of distribution of temperature in the devices investigated. Give data in regard to their input, output, and efficiency. State influence of supply voltage on time necessary for bringing a given amount of water to the boiling-point. Figure comparative cost of heating by gas and by electricity, for the average prices of both, prevalent in the locality.

728. EXPERIMENT 35-B. — Testing an Electric Radiator. — An electric radiator is one of the few devices in which the efficiency is equal to 100 per cent, theoretically as well as practically: All of the electrical input is converted into heat, and this is used for raising the temperature of the surrounding air. The only test, which can be performed on an electric heater, consists in determining the temperature-time curve of the device, and in measuring the total amount of time which it takes for the heater to reach its final temperature. In performing this test read temperatures at various places of the heater, and the temperature of the air at a certain distance from the heater; also note the changes in current due to the variations in the resistance of the heating elements.

Tests relative to the determination of the size of heaters for given conditions, important in the subject of Heating and Ventilation, may also be profitably performed, assuming certain requirements of service.

Report the results of the tests: Figure out theoretically what should be the resistance and the current consumption of a 110-volt air heater, sufficient to raise the temperature of Q cu. ft. of air at a rate of t degrees Fahrenheit in one hour. The air is assumed to be at the ordinary room temperature and atmospheric pressure; moreover, it is supposed that there is no loss of heat through the walls.

729. EXPERIMENT 35-C. — Testing an Electric Soldering Iron. — The purpose of the experiment is to illustrate the use and the advantages of an electrical soldering iron (Fig. 520); also to determine

the cost of its operation. The current is switched on and the input measured every few seconds, until a temperature is reached sufficient for soldering. Have a sufficient supply of small pieces of wire, brass ribbon, etc., and keep on soldering them for a sufficient length of time, in order to determine the cost of operation per joint.

Report time and power consumption for the first joint, and the same for consecutive joints. Figure out the cost of operation on the basis of a certain price per kilowatt-hour, say ten cents.

730. EXPERIMENT 35-D. — Testing an Electric Flatiron. — The distribution of heat, of importance to the users of electric flatirons (Fig. 521), is determined by means of a suitable pyrometer. The amount of time necessary to reach the required temperature is determined by testing, say every half minute, the ability of the iron to scorch papers; such records are sometimes called *shadowgraphs*. Get impressions while heating the iron, and also in cooling it: one of the good characteristics of a flatiron is that it should hold heat as long as possible.

Report. State the amount of time necessary for heating the iron and the watt-hours required for reaching the working temperature. Give the obtained distribution of temperature, and inclose samples of shadowgraphs. Figure out the cost of operation per hour, on the basis of the price per kilowatt-hour prevalent in the locality.

2. ELECTRIC WELDING.

731. The welding of two pieces of metal is a process by which they are made to cohere strongly, or to hold together as a single piece, when powerfully pressed together. To weld such metals as iron, brass and copper, they must be heated up to very high temperatures, near those at which they become incandescent.

Since metals can be heated to any desired temperature by passing through them a sufficiently large electric current, the idea naturally arose of applying electricity to the process of welding. The advantages of using an electric current rather than an ordinary coal fire, are: The joint can be heated much more quickly; the temperature is easily adjusted to any desired degree; greater cleanliness and a better weld result from the absence of impurities due to the gases of the fuel.

732. Description of an Electric Welder. — The operation of the electric welder may be understood from Fig. 523. The device is, in principle, an ordinary alternating-current transformer. The primary winding P may be wound for any commercial voltage (110 volts, 220 volts, 500 volts, etc.); the secondary S consists of one turn of heavy copper bar. The secondary circuit is completed by the pieces M to be

welded; they are fastened in the clamps *CC* and pressed against each other by the weight *W*. If the apparatus is intended to be used continually, the secondary turn is made hollow, and cooling water is circulated through it.

The reason for using alternating current for welding, and particularly for using a transformer of this construction, is as follows: The resistance of two pieces to be welded is very low, but it takes a heavy current to bring them to the required high temperature. Thus, a *heavy current at a low voltage* is needed for welding. The easiest way to produce such currents is by means of a transformer, since by selecting a proper ratio of the number of turns, primary and secondary, the primary current can be increased any desired number of times, with a corresponding reduction of the voltage. Suppose, for example, the primary winding

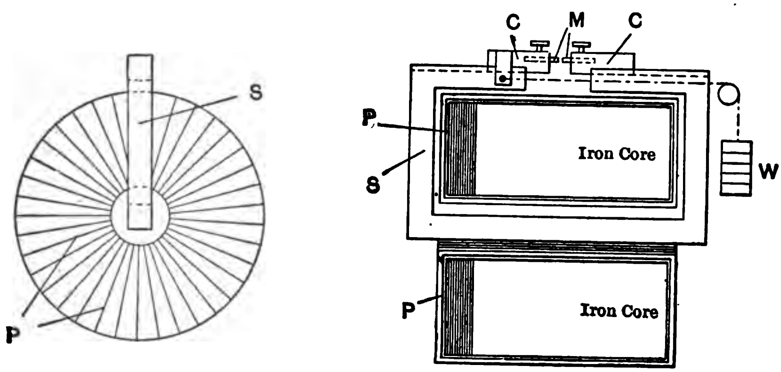


FIG. 523. Electric welder.

to consist of 250 turns, and to be connected to a 500-volt supply. With a single turn in the secondary the secondary voltage will be only 2 volts. At the same time, with the primary current of, say, 10 amperes, the secondary current will be 2500 amperes, which is sufficient for welding comparatively large pieces.

To secure uniform results, the following automatic feature is added to the above welder. The weight *W* is adjusted so as to get the best results for a given operation, and an auxiliary electrical contact is placed near the movable clamp *C*. The operator clamps the pieces to be welded and closes the primary circuit. As soon as the joint becomes soft and the clamp begins to yield, it closes the above contact. This actuates the circuit-breaker, and opens the primary circuit. In this way overheating and waste of power are avoided, and the apparatus can be intrusted to an inexperienced man.

733. Principal Applications. — Electric welding is used to a considerable extent in various metal industries, especially for articles manufactured in large quantities, where the same operation is performed continually. Carriage tires, wheel spokes, axles, etc., are economically welded by this process; pieces of wire and cable are joined in a continuous length; heavy pipes and bars are locally heated to be bent to any desired shape. It is possible to obtain an electrically welded joint of nearly the same mechanical strength as the welded bars themselves.

Large electric welders are used to some extent for joining together rails on electrically operated railways. Rails are commonly used as a return circuit for electric current operating the cars. Therefore a good electrical contact between the rails is essential in order to reduce the voltage drop and the losses; also to prevent electrolysis of water and gas-pipes by stray electric currents. The usual method of connecting rails is by means of *bonds*, or copper strips of different shape. Some engineers prefer to have a *continuous* rail by welding all the joints; electric welders are used for this purpose. A discussion of the comparative advantages of bonding and welding rails is out of place here, and the student is referred to the special electric-railway literature.*

A track-welding car, which is an ordinary motor car provided with a large welding transformer and a motor-generator set, for converting the 500-volt direct current from the trolley wire into the alternating current necessary for welding, is required for welding rails. The two ends to be welded are clamped into the transformer on the track and pressed together by hydraulic pressure of a hand pump. Then the current is put on and the welding effected, as described above for smaller pieces.

734. EXPERIMENT 35-E. — Exercises in Electric Welding. — The student should begin the experiment by welding together two pieces of a metal rod of a certain size and material. This should be done at different values of the applied voltage, beginning with the lowest voltage at which the welding can be accomplished. The variables of practical interest in this test are: The amount of time required to weld a joint; kilowatt-hour input; average current and watts and their fluctuations; power factor; quality of the weld and its mechanical strength. Having an ammeter, a voltmeter and a wattmeter in the primary circuit, all the necessary electrical data can be readily obtained.

* It may be mentioned here that electric welding now has a serious competitor in Goldschmidt's thermit, which is an aluminum compound burning at a very high temperature. A mould is made around the place to be welded, and the molten thermit is poured into the mould. The temperature thus obtained is sufficient to weld two pieces of rail.

A testing machine should be provided for measuring the tensile strength of the joint and comparing it to that of the material itself. The pressure exerted on the pieces during the welding may also affect the results, and should be noted and varied within certain limits. In order to get reliable results, the main switch must be opened the very moment the welding is affected, as would be the case in an automatic welder. It may occur that minimum time corresponds to one voltage, minimum power to another, etc.; the most advantageous voltage can then be selected in each case, according to the importance ascribed to these different factors.

After reliable average data have been obtained with samples of a certain size, take samples of the same material, having different cross-sections, and weld them, in order to see the influence of the cross-section. Try also to weld samples of different materials.

Report the results as to power consumption, time, tensile strength, influence of cross-section, etc., and state your conclusions. Figure out cost per weld at a certain rate for power supply.

735. EXPERIMENT 35-F. — Test of a Welding Transformer. — The purpose of the experiment is the determination of the electrical efficiency of a welding transformer (Fig. 523), or of the proportion of the watts input, which is actually converted into heat at the joint. This is by no means a simple problem; the relations in the secondary circuit being such as to permit no very accurate measurements of volts and amperes, with ordinary commercial ammeters and voltmeters, nor usually of any wattmeter readings. Moreover, the resistance of the secondary circuit is so low, that connecting an ammeter into it appreciably changes the current and the voltage relations. The following method, without any claim to accuracy, gives at least a general idea of the electrical relations in the secondary circuit of a welding transformer.

(1) Measure the secondary voltage on open circuit. This can be done either by using an ordinary alternating-current voltmeter, connected through a step-up shunt transformer (because of the very low voltage); or else, a low-reading hot-wire ammeter can be used as a voltmeter, with some resistance in series if necessary. If the primary winding of the transformer is accessible, or if its number of turns can be determined in some other way, compare the ratio of voltages with the ratio of turns, primary and secondary, as a check.

(2) Measure the ratio of currents, primary and secondary. For this purpose the secondary must be short-circuited through a known low resistance, wound non-inductively and the volts drop across it measured, say with a hot-wire instrument, calibrated as a voltmeter. This

permits one to figure out the secondary current, corresponding to a certain primary current, in other words the current ratio of the transformer. See if this ratio is nearly equal to the inverse ratio of the number of turns, as in ordinary transformers.

(3) Now put into the welder two pieces to be joined together, and read primary volts and amperes, and secondary volts across the joint. From the test (1), secondary induced volts are known; from the test (2), secondary amperes can be calculated. With these data at hand, both the efficiency of the secondary alone, and of the welder as a whole, can be determined. Volts read across the joint, times secondary amperes, give watts developed at the welding place, or useful watts. The ratio of these to the watts input gives the efficiency of the transformer. The ratio of the voltage across the joint to the voltage induced in the secondary gives the efficiency of the secondary, because it shows which part of the induced voltage is available for welding.

As a check, the student should measure the primary resistance by direct current, and determine the iron loss by the wattmeter method (Fig. 162). Then, knowing the primary copper loss and the iron loss, the input into the secondary can be calculated. Subtracting from it the measured output, the difference gives the secondary losses. These losses are comparatively high, because of unfavorable electrical relations in the secondary circuit, and also on account of a comparatively high contact resistance between the secondary itself, the clamps, and the pieces to be welded.

No particular accuracy is expected from this efficiency test; this, however, does not diminish its value. There are many cases in practical engineering, in which only approximate results are obtainable. And yet the engineer has to design, build, and use apparatus on this uncertain foundation.

CHAPTER XXXVI.

INTERIOR ILLUMINATION.

736. Use of Reflectors, Shades and Globes. — The natural distribution of light about an incandescent lamp (Fig. 180) may be considerably improved by the use of proper reflectors and globes. The photometric curves shown in Fig. 528 illustrate this point; the dotted

FIG. 524. Holophane concentrating reflector.

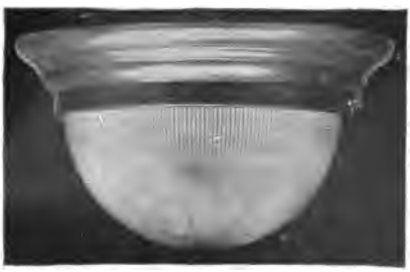


FIG. 525. Ceiling bowl.

FIG. 526. Two-piece sphere supported by chains.

curve gives the distribution of light about a bare 16 candle-power lamp; the elongated curve shows the distribution of light when the same lamp is provided with a reflector shown in Fig. 524. The intensity of light in the vertical direction is increased from 7 to 60 candle-power; a considerable increase in illumination is also obtained in other direc-

tions up to a latitude of 60 degrees. Beyond this, the illumination is reduced. This, however, is no objection if the light is needed chiefly under the lamp, say for the illumination of a table. The gain in this case is evident, since it would take at least three or four bare lamps to produce the same illumination on the table, and much light would be wasted where it is not needed.

Different distribution of light, as required in various practical cases, is obtained by a proper design of globes and reflectors. Three different kinds of distribution of light are shown in Fig. 527; they are obtained

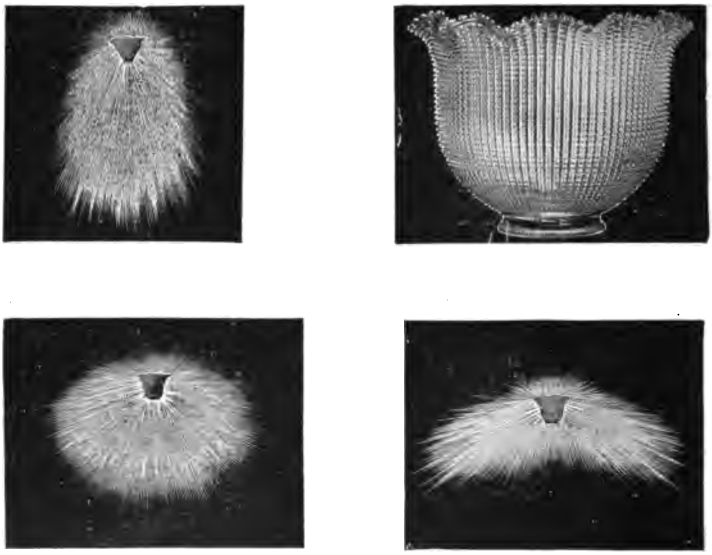


FIG. 527. One of the forms of Holophane prismatic-glass globes, and illuminating effects produced by properly shaping the external prisms.

with various glass globes of the type shown in the upper right-hand corner of the sketch. The globe has the same general form in all cases: its outer surface is made into series of small prisms. By properly shaping these prisms, light is thrown in any desired direction. The globe shown in the upper left-hand corner may be properly used when maximum light must be thrown downward, for instance, in chandeliers over reading-tables. The one shown under it is suitable for general illumination, the distribution of light being much more uniform. The globe in the lower right-hand corner throws maximum light at from 10 degrees to 15 degrees below the horizontal, and is designed to light large areas, streets, etc.

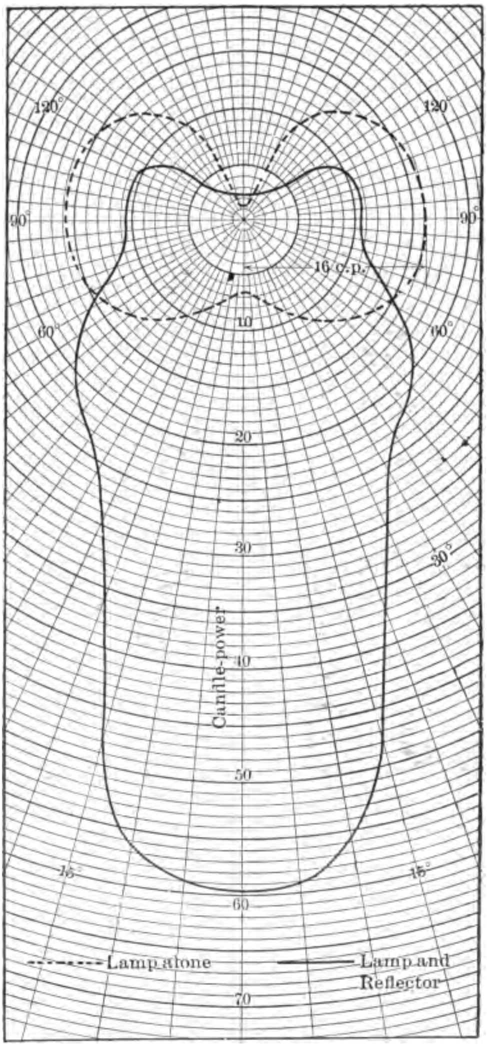


FIG. 528. The photometric curve of the Holophane reflector shown in Fig. 524.

A great variety of shades, globes and reflectors are used in connection with incandescent lamps, the determining factors in the selection being the purpose of the illumination, artistic requirements and the price. The most common reflectors and globes are shown in Figs. 529 and 530. The globes and reflectors in Fig. 529 are made of opal glass, and according to their form are called dome, cone, bell reflectors, flat reflectors, etc. Those with grooves on the surface are distinguished by

FIG. 529. Some common types of opal-glass globes and reflectors.

the word "fluted." Thus, the third reflector in the upper row, counting from the left, is known in the trade as the "fluted opal cone reflector." The shades shown in Fig. 530 are usually made of sheet iron, sometimes of cardboard. The two upper ones are called cone shades, the lower one between them is a flat shade, that to the right a parabolic shade (or reflector). Metal shades are used in factories,

FIG. 530. Metal shades and reflectors.

drafting-rooms, etc., where light must be concentrated on a limited surface; general illumination is usually supplied by other lamps near the ceiling. Glass reflectors allow the concentration of light, and at the same time let sufficient light through for general illumination.

737. Holophane Prismatic-Glass Globes and Reflectors. — Some of the disadvantages of the above-described globes and reflectors are: (a) they absorb a considerable amount of light; (b) light is not sufficiently diffused; (c) illumination can be concentrated in desired directions to a limited extent only. These defects are eliminated to

a considerable degree in the so-called "Holophane" prismatic-glass globes and reflectors, shown in Figs. 524 to 527.

The name "Holophane" was taken from two Greek words meaning "all-light." The underlying principles, on which these globes are built, have been developed by Messrs. Blondel and Psaroudaki in France. Holophane *globes* are made of high quality pressed glass, and have both internal and external surfaces made into series of small prisms of different shapes and sizes. The function of the internal prisms (Fig. 531) is to diffuse the light given out by the lamp. Each ray, such as *ab*, is broken up into at least two rays *bcd* and *befg*, so that the eye, following back each component, is unable to see the actual, concentrated source of light, but the whole globe becomes a source of diffused light. The external prisms (Fig. 532) have in general four faces; through some of

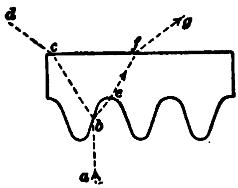


FIG. 531. Internal prisms on Holophane globes.

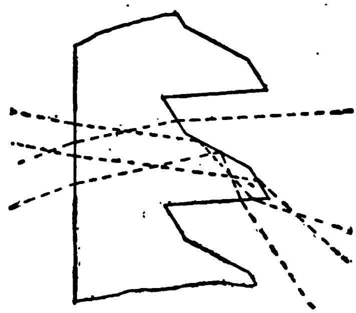


FIG. 532. External prisms on Holophane globes.

these faces light passes with a simple refraction. On others it suffers a total reflection and goes out through one of the other faces. It is absolutely essential that the prisms be accurately designed; otherwise some of the light is apt to be thrown back into the globe, thereby decreasing the efficiency.

Holophane *reflectors* (Fig. 524) are based on a somewhat different principle; they are particularly adapted for throwing light downward, or if desired, at an angle of about 45 degrees, at the same time giving sufficient general illumination. They are smooth on the inside, and have a series of right-angle prisms on the outside. These prisms offer to the light a total reflecting surface; it is thus possible to throw the light strongly below the horizontal, with an extremely small loss from absorption. At the same time, some of the light passes through the top and bottom of each prism, thus allowing sufficient light to illuminate the ceiling.

Holophane globes and reflectors are made in a great many types to suit various purposes and different artistic requirements. For most of them photometric curves, like the one in Fig. 528, are known, so that it is possible to select in each case the most suitable.

738. EXPERIMENT 36-A. — Influence of Globes, Shades and Reflectors on the Distribution of Light about an Incandescent Lamp. — Place a bare incandescent lamp in a photometer, and obtain its curve of distribution of light, as in § 197. Then repeat the same test with representative types of globes, shades and reflectors described in §§ 736 and 737. It is also advisable to take photometric curves of one and the same globe with lamps having markedly different photometric curves. If an integrating photometer is available, absorption due to a globe may be determined directly by measuring the mean spherical candle-power with and without the globe.

Report. Plot photometric curves of the globes and reflectors tested, as in Fig. 528. Figure out the mean spherical intensity (§§ 195 and 196) from a few representative curves, and compare it to the mean spherical intensity of the bare lamp. The ratio will give per cent absorption of light due to the globes. Give your opinion as to the relative quality of different types tested, and the cases where they should be used.*

739. Foot-Candle as a Unit of Illumination. — If an 8 candle-power lamp be placed two feet above a desk, the lamp gives a certain illumination on a small sheet of paper placed directly under it on the desk. A 32 candle-power lamp placed four feet above the desk, or a 2 candle-power lamp at a distance of one foot from the desk will give practically the same illumination of the sheet of paper. The intensity of illumination may be understood here, for the time being, as the facility with which some print may be read on the piece of paper. Thus, the intensity of illumination of a surface depends on the candle-power of the lamp and on its distance from the surface. *Intensity of illumination produced by a source of one candle-power at a distance of one foot from it, on a small surface perpendicular to the ray, is called the foot-candle.* According to the fundamental law of optics, illumination decreases inversely as the square of the distance: therefore, it takes a 4 candle-

* In case of concentrating reflectors, the law of inverse squares does not hold, and consequently the photometric curve varies for different lengths of bars: the mean spherical candle-power obtained by the Rousseau diagram is apt to depart widely from the truth. For example, a mirror reflector, which has a diamond surface effect, has been found to have an efficiency of 98 per cent, whereas the true efficiency cannot be much over 80 per cent, owing to the fact that the light rays must pass through two layers of glass, and also that the silvering used in this reflector does not have a greater reflecting power than 85 per cent.

power lamp to produce the same illumination at a distance of 2 feet, 9 candle-power at 3 feet, 16 candle-power at 4 feet, etc. In this way illumination produced by a source of light of known luminous intensity can be expressed numerically in foot-candles. Take, for instance, a 16 candle-power lamp with a Holophane reflector, shown in Figs. 524 and 528; let this lamp be placed at a distance of 4 feet above a desk. The vertical intensity of light is about 60 candle-power; therefore, if the lamp were placed at a distance of one foot above the desk, it would produce an illumination of 60 foot-candles. The actual distance being 4 feet, the illumination is reduced $4^2 = 16$ times, or

$$\text{intensity of illumination} = \frac{60}{4^2} = 3.75 \text{ foot-candles.}$$

In general, if J is the luminous intensity of a lamp, in candle-power, and d the distance in feet, from a small perpendicular surface illuminated by the lamp (or the distance from lamp to surface illumined), the normal intensity of illumination $= \frac{J}{d^2}$ (in foot-candles).

740. Calculation of Illumination. — The above formula gives the intensity of illumination when the surface to be illuminated is perpendicular to the direction of the rays of light. If the surface is not perpendicular, the illumination is reduced as the cosine of the angle θ of deviation from the normal. This follows from the fact that the number of rays of light per unit surface is reduced in this proportion, for obvious geometrical reasons. Thus, in general,

$$\text{intensity of illumination} = \frac{J}{d^2} \cdot \text{Cos}\,\theta \qquad (1)$$

In practice, illumination is usually calculated for the floor, or for a horizontal plane a few feet above the floor. For such cases the above formula may be modified as follows: Let h be the vertical distance between the center of the lamp and the horizontal plane for which the illumination is to be determined; we have $h = d \cdot \text{Cos}\,\theta$. Substituting the value of d into the above formula, we find

$$\text{horizontal intensity of illumination} = \frac{J}{h^2}\,\text{Cos}^3\,\theta \text{ (in foot-candles).} \qquad (2)$$

Take, as an example, the lamp with a reflector, shown in Fig. 528, and assume it to be placed 8 feet above the floor. Let it be required to find the horizontal illumination in a plane 3 feet above the floor, at a point such that the rays from the lamp make an angle of 30 degrees

with the vertical. From the photometric curve we find that the luminous intensity in this direction $J = 26$ candle-power; the horizontal illumination is equal to

$$\frac{26}{(8-3)^2}\,\mathrm{Cos}^3\,30° = 1.04 \times 0.649 = 0.675 \text{ foot-candles.}$$

The normal, or maximum illumination at the same point is

$$\frac{26}{(8-3)^2}\,\mathrm{Cos}^2\,30° = 0.78 \text{ foot-candles.}$$

This latter illumination could be obtained, for instance, upon a book at the point under consideration, if held in the most advantageous

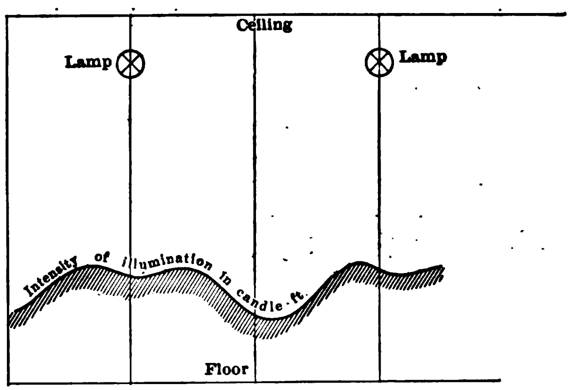


FIG. 533. Sample of an illumination curve.

position with respect to the lamp. The horizontal illumination directly under the lamp is

$$\frac{60}{(8-3)^2} = 2.4 \text{ foot-candles.}$$

741. Illumination Curves. — If there is more than one lamp in the room, the illumination produced by each one is calculated separately, and the results added from point to point. Thus, the room shown in Fig. 533 is illuminated by rows of lamps placed near the ceiling. The height of all the lamps above the floor being the same, the horizontal illumination at any point, according to the expression (2), is represented by the formula

$$\text{horizontal illumination} = \frac{1}{h^2}\sum J\,\mathrm{Cos}^3\,\theta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2a)$$

The ordinates of the curve shown in the sketch give the intensities of illumination: the points of maximum illumination lie right below the lamps, points of minimum illumination between the lamps.

The illumination curves are different in different vertical planes of the room: therefore, it is customary to supplement them by curves showing distribution of illumination in the horizontal plane. These latter curves connect points of equal illumination in the room, and may be properly called "isophotal" curves, by analogy with "isothermal" curves.

In planning the illumination of a room, the designer assumes certain intensities of illumination, according to the requirements of the room, and places the lamps tentatively, until the desired intensities are approximately obtained. At the same time lamps must be placed so as

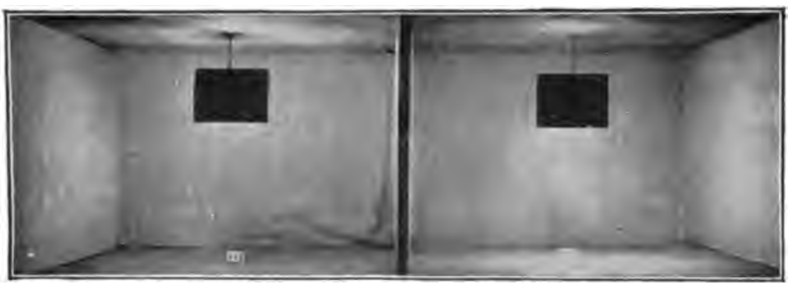


FIG. 534. Two dark rooms for demonstrating relative advantages of various globes and reflectors.

to satisfy the artistic requirements and the convenience of wiring and control.

The actual values of illumination are somewhat modified by reflection from walls and ceiling. It is not possible at the present state of the art to give the necessary correction, the more so that the influence of reflected light varies greatly with the position of the lamps, the color and the state of surface of the walls, and the proportions of the room. Professional illuminating engineers assume in each case some empirical correction on the basis of their previous experience.

742. EXPERIMENT 36-B. — Demonstration Room Tests. — The foot-candles illumination at various points of a room may be measured with sufficient accuracy by photometers described below. It is desired, however, that before undertaking such accurate measurements, the student should observe the most important effects of illumination in their practical, physiological effect upon the eye. Simple demonstration tests are conveniently performed by using two small identical rooms

(Fig. 534) built side by side, within a larger dark room. The rooms may conveniently have a floor area of 4½ by 4½ feet, and be about 3 feet high; they must be separated from each other by a partition. The rooms are open in front, so that the effect of illumination may be observed or photographed.

A bare incandescent lamp is placed in one room, an identical lamp provided with a shade or a globe is placed in the other room. The lamps themselves are shaded from the observer by a piece of black cardboard. The difference in illumination is clearly noticeable in the figure.* To make it more marked, a piece of paper is put on the floor, with letters of different size, such as are used in oculists' offices. To obtain a lasting record, the two rooms are photographed on one plate. By changing the location and the size of the lamps, by putting different globes and reflectors, by changing the color and the state of surface of the walls and the ceiling, the student will get a practical conception of the effect of these factors on illumination.

In deriving conclusions from the photographs, care should be taken to compare the two sides of the same photograph only, and not the absolute intensities of illumination in different photographs. The latter may show different relative illumination than is actually the case, because of differences in the plates themselves, and of the peculiar conditions of illumination when pictures are taken.

MEASUREMENT OF ILLUMINATION

743. The problem of illumination consists (a) in determining the necessary number of lamps and their candle-power; (b) in properly locating the lamps in the room; (c) in selecting suitable reflectors or globes. Lighting of small rooms, or places where the requirements are not strict, is designed on the basis of simple every-day experience. Lighting of large public halls, theaters, churches, etc., requires a considerable study in each individual case. Designing an efficient illumination is in many respects an art, which could hardly be discussed here. There are, however, certain fundamental principles which admit of numerical calculations, and which can be verified experimentally. Some of these experiments and tests are described below.

Illumination in foot-candles is measured by photometers of somewhat different construction than those described in Chapter IX. The "illumination" photometers must be portable and self-contained so as to be placed at the points where it is desired to determine the illumination.

* Fig. 534 is taken from Cravath and Lansingh's book, entitled *Practical Illumination*, by courtesy of the McGraw Publishing Company.

The classical Weber photometer (§ 746) has been used for such tests for many years. Attention is here called to a convenient little instrument, devised for the same purpose by the late Mr. J. T. Marshall of the General Electric Company.

744. The Marshall Luminometer. — The instrument is shown diagrammatically in Fig. 535. It is based on the fact that the resistance of an incandescent lamp changes with its candle-power, so that once calibrated, the candle-power may be determined by simply measuring the resistance of the lamp. A low candle-power, low-voltage tungsten lamp is used in the luminometer, because of the constancy of its candle-power with time, and also because it has an appreciable temperature

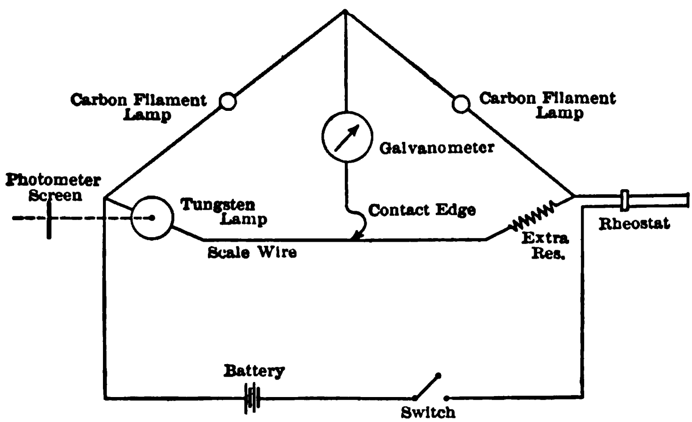


FIG. 535. The Marshall luminometer.

coefficient. The tungsten lamp illuminates a Bunsen screen (§ 185) placed at a constant distance from it, and constituting a part of the instrument itself. This illumination is balanced by the illumination of the other side of the screen, it being placed at the point and in the direction where it is desired to measure the illumination. The balance is obtained by varying the voltage of the tungsten lamp by the rheostat shown in the sketch.

The resistance of the tungsten lamp is measured by an arrangement similar to an ordinary slide-wire Wheatstone bridge (Fig. 11). Two high-resistance carbon filament lamps are used as ratio resistances; the scale is calibrated direct in foot-candles. The calibration is done by presenting the screen successively to different known foot-candles of illumination.

To determine the illumination at a certain point, the instrument is

set so that the photometric screen is at the required point, and in the desired plane, say horizontal. The rheostat in series with the battery is adjusted until an equal illumination is obtained on both sides of the screen. Then the exploring contact edge on one of the galvanometer leads is moved along the slide-wire until the galvanometer returns to zero. Foot-candles of illumination are read directly on the scale at this point. All the parts of the instrument, including the battery, the galvanometer and the rheostat, are mounted in a box, so that the instrument is absolutely self-contained, and may be used in any location.

745. EXPERIMENT 36-C. — Calibration and Use of the Marshall Luminometer. — The device (Fig. 535) is calibrated by means of a standard incandescent lamp. The lamp is placed at definite distances from the screen, say, 2, 4, 6, etc., feet, and a balance is obtained, as explained above. Let, for instance, a 16 candle-power lamp be placed at a distance of 2 feet from the luminometer screen; the illumination of the screen is $16 \div (2)^2 = 4$ foot-candles. The point of the scale at which the galvanometer balance is obtained must be marked 4. Having calibrated the instrument, it may be used for a study of distribution of illumination in a room (Fig. 533). In this particular experiment, it is sufficient to investigate the simplest case, of a room lighted by one lamp in the center. Measurements are conveniently made in a horizontal plane, about 3 feet above the floor. Take first a bare lamp and determine horizontal intensities of illumination, from a point under the lamp, to one of the walls. Repeat the same measurements with the lamp fixed at different heights, and also provided in succession with two or three different kinds of globes and reflectors. Use preferably a lamp and a globe of which the photometric curves are known (Fig. 528). If possible, this experiment should be performed in two identical rooms, in one of which the walls and the ceiling are painted dull black, while in the other they offer light-reflecting surfaces. The same effect can be obtained by temporarily covering the walls and the ceiling with black cloth.

Report. (1) Give the calibration curve of the luminometer. (2) Plot curves of horizontal illumination. (3) Check a few points with the theoretical illumination, calculated as in § 740. (4) Discuss the influence of the walls and ceiling.

746. The Weber Photometer. — This photometer, like the above-described luminometer, is primarily intended for measuring illumination, though it can also be used for measuring luminous intensities of primary sources of light. The instrument is shown diagrammatically

in Fig. 536; a perspective view is given in Fig. 537. We shall describe it first as it is applied for measurement of the luminous intensity of a lamp, and then will show how to use it for measurements of secondary illumination. The lamp L_1, whose candle-power it is desired to determine, illuminates the opal-glass screen a_1. The standard benzine lamp L_2* illuminates another opal-glass plate a_2. The intensities of illumi-

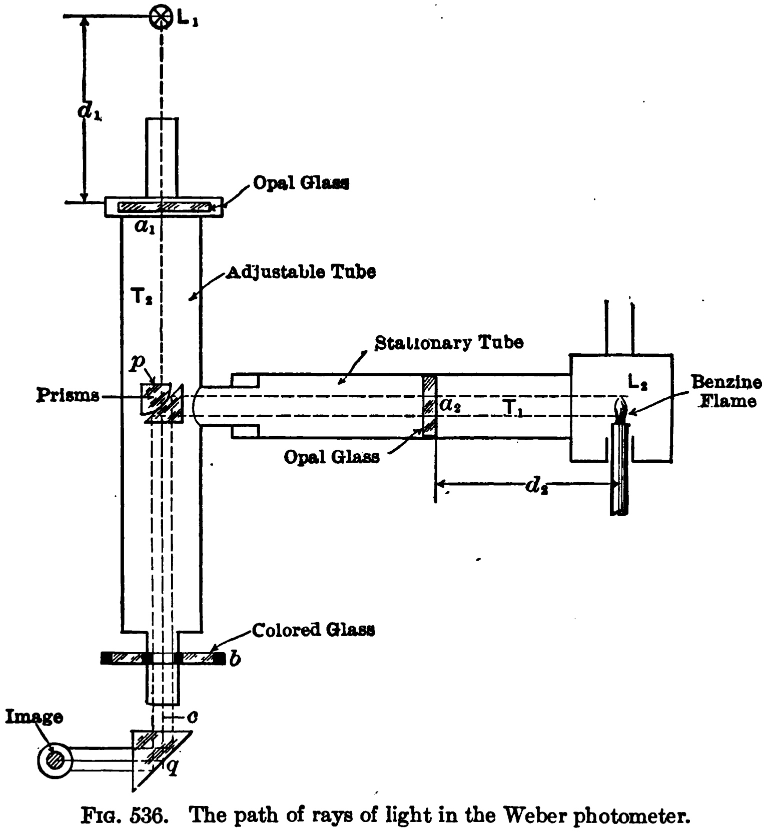


FIG. 536. The path of rays of light in the Weber photometer.

nation of the two plates are compared from c, through the Lummer-Brodhun prisms p (§ 191). The plate a_2 is moved along the tube T_2 until a photometric balance is obtained (Figs. 172 and 178).

The illumination of the plate a_1 is $J_1 \div d_1^2$, where J_1 is the candle-power of the lamp L_1 and d_1 its distance from the plate a_1. Only part

* The original benzine lamp may be conveniently replaced in some cases by a small low-voltage tungsten or carbon incandescent lamp supplied with current from a portable battery, as in the above-described Marshall luminometer.

of this light passes through the plate, so that the above expression must be multiplied by a constant C_1. A similar expression may be written

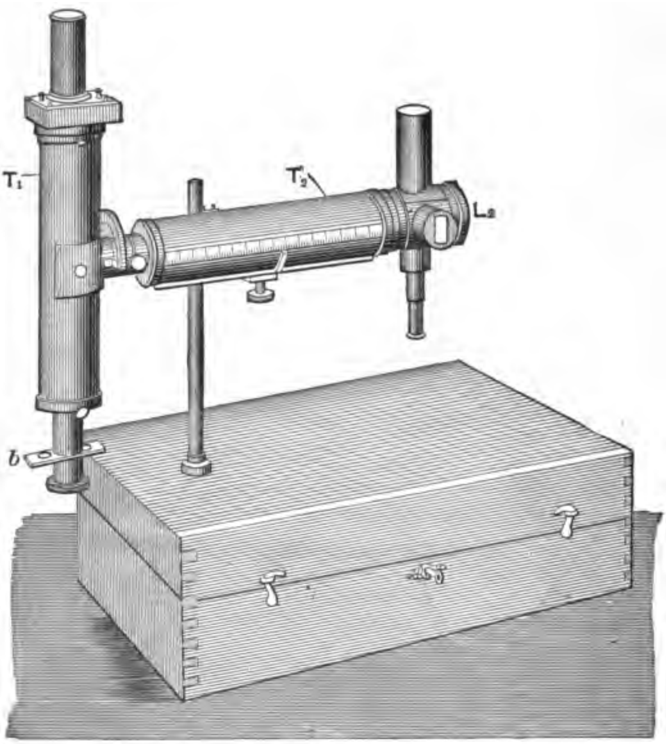


FIG. 537. The Weber photometer.

for the plate a_2; when the observer sees the two plates equally illuminated, we have

$$C_1 \cdot \frac{J_1}{d_1^2} = C_2 \cdot \frac{J_2}{d_2^2},$$

or

$$J_1 = C\left(\frac{d_1}{d_2}\right)^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

The constant C comprises the candle-power of the benzine flame, and the constants C_1 and C_2 of both opal plates. The constant C is determined empirically, by using a standard lamp in place of L_1. A few plates a_1, of different translucency, are supplied with the instrument, for use with sources of different intensity.

The tube T_1 can be pointed in any desired direction and fastened by a clamping device. The angle is indicated on the divided sector seen in Fig. 537. When T_1 is pointed upward, it would be impracticable to take observations at c; a prism q is used in this case, and the observer's eye is placed at the point marked "Image." The eye-piece b is provided with three circular openings: one is covered with a piece of red glass, another with a piece of green glass; the middle opening is left blank. Colored glass is used when the lights under comparison are of different tints. Then they are compared, once with red glass and then with the green glass. With the instrument are given tables from which the true ratio of lights may be calculated from the two settings. A flicker photometer (§ 192) affords, however, a more reliable means for comparing lights of different color. The plate a_2 is moved by a rack and pinion; the operating knob is seen in Fig. 537 under the tube T_2; distances d_2 from the center of the benzine flame are read on the horizontal scale.

The same photometer may be used for the determination of secondary illumination, by placing the instrument so that the opal-glass plate a_1 is at the desired point and in the desired direction. The small tube above a_1 should be removed. When photometric balance is obtained, we have, according to (3),

$$\text{illumination of } a_1 = \frac{J_1}{d_1{}^2} = C\left(\frac{1}{d_2}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

so that knowing C, the illumination can be calculated in foot-candles.

If it is not convenient to place a_1 in the desired location, a diffusing white screen (usually supplied with the instrument) is placed there. The plate a_1 is removed altogether, and the illumination of the white screen is compared to that of a_2. The formula is again

$$\text{illumination of the white screen} = C'\left(\frac{1}{d_2}\right)^2 \quad . \quad . \quad . \quad (5)$$

where C' is another constant: it is determined by illuminating the white screen with a standard lamp at a known distance.

For a more detailed description of the Weber photometer, and instructions for its use, see Stine, "Photometric Measurements," p. 78.

747. EXPERIMENT 36-D. — Calibration and Use of the Weber Photometer. — The photometer (Figs. 536 and 537) is calibrated by means of a standard incandescent lamp. The lamp is placed at known distances $d_1 = 1, 2, 3$, etc., feet from the upper glass plate a_1, and photometric balance is obtained. All quantities in the expressions (3) and (4) being known, the constant C may be calculated. Calibrate in this way a few plates supplied with the instrument. Before using the

photometer, see that the benzine lamp is adjusted according to the directions given by the manufacturer, especially that the height of the flame is correct. Have the lamp burning for 10 or 15 minutes before beginning the measurements. Determine the constants of the instrument when a small incandescent lamp is used in place of the benzine flame. After this, determine the constant C' of the white screen supplied with the instrument, and the limits within which this constant is independent of the distance of the screen and of the angle at which the photometer is placed relative to the screen. Take a few readings with the red and the green glasses, and see to what extent the settings are different from those obtained with the blank aperture.

Having calibrated the instrument, it may be used for exploring the illumination of a room, in the same way as in § 745. As another application, determine the distribution of illumination produced in a large room by daylight. Also measure the illumination on a street lighted with arc lamps. The report is similar to that required in § 745.

748. EXPERIMENT 36-E. — Determination of Standard Values (Norms) of Illumination. — When designing the illumination of a room, some basis must be had for determining the number and the size of lamps and their location. This is done by assuming so and so many candles per square foot of the floor, or per cubic foot of the room. Or else values are given in terms of foot-candles of illumination. Careful illuminating engineers usually check their designs by means of all three types of units. The values vary according to the size and the use of the room, quality of the illumination desired, etc. The experiment described below is intended to develop the judgment of the student in this respect.

The tests should be performed in the evening, in a medium-sized room. The wiring must be planned, so that it is easy to vary the position and the number of lamps. Assume the room to be intended for a certain purpose, say for lectures: place a few lamps with reflectors or globes in the most efficient way. Vary their number and distribution, gradually passing through the degrees of illumination, which may be called: dull, medium, good, bright, and brilliant. Determine in each case candle-power per square foot and per cubic foot, also measure the intensity of illumination in foot-candles, as in §§ 745 and 747. In performing these tests, keep in mind that the purpose is not to light the room actually, but to get standards (norms) for design; therefore use your judgment in modifying the norms where the conditions in the room are different from those actually met with in practice.

After this, determine in the same room the norms for various other

purposes: for lighting a parlor, a dining-hall, a library, a store, a drafting-room, an office, a workshop, etc. In each case determine the limits of illumination that might be characterized as dull, good, and brilliant. Also distinguish between a *general* illumination and the illumination for a *specific purpose*, such as lighting a dining-room table, a desk, a counter, etc.

In performing this experiment the student must rely entirely on his own judgment and try to develop it in the matters of illumination. Care should be taken to rest one's eyes from time to time, and avoid quick changes in illumination, which may bias the judgment.

749. EXPERIMENT 36-F. — Exercises in Lighting Rooms. — The exercises specified below are intended for a practical application of the principles of illumination treated in §§ 736 to 748. Begin with a rather small room, suitable for use as a living-room, a parlor, a dining-room, or a small office. Place a few incandescent lamps, as you think best, for the desired quantity and distribution of light. Use the norms of illumination determined as in § 748, or taken from a hand-book. Measure the actual illumination at a few points by means of the Marshall luminometer, or the Weber photometer, and compare it to the calculated intensity of illumination. Try a few different arrangements of lamps, with various shades and globes; compare critically the results obtained, in regard to efficiency, convenience, and the artistic appearance. Work in one room until a satisfactory solution of the problem is found. Then take a larger room, suitable for public gatherings, or to be used as a restaurant, a workshop, etc., and again work out the problem of its illumination. Good practical suggestions for lighting rooms may be found in the second part of a book on *Practical Illumination* by Cravath and Lansingh, beginning with Chapter XVI.

Report. Make drawings of the rooms, showing the most efficient location for the lamps; mark the kind of lamps and reflectors used. Give the measured illumination, in the form of curves shown in Fig. 533, as well as isophotal curves. Check the illumination by means of photometric curves (§ 740); compare the actual amount of light used with the values deduced in § 748.

750. EXPERIMENT 36-G. — Effect of Color of Illuminants. — This experiment is intended to be a demonstration, rather than an accurate test, the effect of color being purely subjective. Accurate investigations on the effect of color belong in the domain of spectrophotometry, which so far has not been applied for practical purposes. The question of color is of importance in dry-goods stores and in places where chemical reactions are watched by their color; also in luxurious

residences, picture galleries, etc. Take a few pieces of a fabric, or a few bottles of some colored chemical, say red, and place them side by side in inclosures, each illuminated by a different kind of light. As such may be taken: a kerosene lamp, a gas burner with and without mantle, an acetylene burner, a Nernst lamp, and a few incandescent lamps with carbon, tantalum and tungsten filaments. If possible, use also an enclosed arc lamp, a luminous (flaming) arc, and a mercury-vapor lamp. Observe the differences in color of the test pieces; note the effect of a white and of a black background. Try to have the intensity of illumination as far as possible the same in all cases, by interposing opal screens, or smoked glass. Compare in this way samples of different color — yellow, green, blue, etc. — and see which color is distorted the most with each kind of illuminant. Describe your findings as definitely as possible.

CHAPTER XXXVII.

SAFETY OF ELECTRIC PLANTS.

751. ELECTRICAL machinery and wiring, if improperly or carelessly installed, may become a source of annoyance, fire hazard, and danger to life. In order to minimize the chance of such disturbances, and to make electric installations reliable and safe, a code of rules and regulations was drawn up in 1897, by the united efforts of fire insurance companies and various engineering and business associations, interested in the development of electrical industry. These rules, commonly known as the "National Electrical Code," or as Fire Underwriters' Rules, are at present recommended and adopted by the following associations:

American Institute of Architects.
American Institute of Electrical Engineers.
American Society of Mechanical Engineers.
American Institute of Mining Engineers.
American Street Railway Association.
Associated Factory Mutual Fire Insurance Companies.
Association of Edison Illuminating Companies.
International Association of Fire Engineers.
International Association of Municipal Electricians.
National Board of Fire Underwriters.
National Electric Light Association.
National Electrical Contractors' Association.
Underwriters' National Electric Association.

The rules are yearly revised by the delegates of the above associations, so as to be up to date with the progress of the art. They are published in book form, and may also be found reprinted in various pocket-books and text-books (for instance, in *Foster's Pocket-book*). A very convenient edition, with explanatory notes and examples, is that of the Associated Mutual Fire Insurance Companies.

It must be understood that these rules have no legal power, as do the corresponding rules in some countries; but being adopted by practically all the insurance, electrical, mechanical, architectural and allied interests of the country, their authority is acknowledged by all reliable

manufacturers, contractors and consulting engineers, who strictly adhere to them. Moreover, it is difficult at present to insure a building, unless its electrical installation is put up in accordance with the National Electrical Code, or some similar rules.

In all contracts for electrical work it is advisable to introduce a clause to the effect, that all work must be done strictly in accordance with the National Electrical Code, and that no fittings shall be used, not found in the latest edition of the *List of Approved Fittings* (published semi-annually). This clause insures good workmanship and materials, and in case of a litigation one has the support of the competent and impartial National Board of Fire Underwriters.

752. Subdivision of the Rules.—The general plan of the National Electrical Code is as follows:

CLASS A.—STATIONS AND DYNAMO ROOMS. Includes central stations; generator, motor and storage-battery rooms; transformer substations, etc. Rules 1 to 11.

CLASS B.—OUTSIDE WORK, all systems and voltages. Rules 12 to 13A.

CLASS C.—INSIDE WORK:—
General Rules, all systems and voltages. Rules 14 to 17.
Constant-Current Systems. Rules 18 to 20.
Constant-Potential Systems:—
General Rules, all voltages. Rules 21 to 23.
Low-Potential Systems, 550 volts or less. Rules 24 to 34.
High-Potential Systems, 550 to 3500 volts. Rules 35 to 37.
Extra-High-Potential Systems, over 3500 volts. Rules 38 and 39.

CLASS D.—FITTINGS, MATERIALS, AND DETAILS OF CONSTRUCTION, all systems and voltages. Rules 40 to 63.

CLASS E.—MISCELLANEOUS. Rules 64 to 67.

CLASS F.—MARINE WORK. Rules 68 to 83.

With the exception of the Classes E and F, which are of less importance for general work, the rest of the rules can be subdivided in two large sections: (1) *installations* (classes A, B and C), and (2) *fittings and supplies* (class D). In the latter class rules will be found prescribing details of construction of switches, fuses, lamp sockets, wire, etc., *per se*. The other classes contain regulations as to how these supplies must be installed, and which types are permitted in various cases.

The *List of Approved Electrical Fittings*, published semi-annually as a supplement to the National Electrical Code, contains the names

of firms, trade marks, types and styles of fittings, manufactured in accordance with the Fire Underwriters' rules. When purchasing or specifying such supplies, it is not necessary to compare them each time with the National Electrical Code, since they are manufactured in accordance with the requirements of this code.

In view of the importance of the National Electrical Code, it is essential for every electrical engineer to become familiar at least with the general arrangement of the rules, and with their principal requirements. The simplest way to begin this work is to go over an electrical installation with the Underwriters' rules in hand, and to compare different parts of the installation with the codes as though assuming the duties of a fire-insurance inspector.

In accordance with the above subdivision of the rules, the laboratory exercises are also divided into two parts: Inspection of supplies, and inspection of installations.

753. EXPERIMENT 37-A. — Inspection of Supplies. — This work is covered by class D of the National Electrical Code. The following are the supplies most used, and on the quality of which the safety and the reliability of service essentially depend: Insulated wire and cables, conduits, cleats and knobs (for supporting wire), switches, cut-outs and fuses, cut-out cabinets, rosettes and lamp sockets. Samples of these supplies should be provided in the laboratory, and the students are to inspect as many of them as time will permit. The inspection consists in taking a device apart, or at least opening it if necessary, and in comparing the details of its construction and the materials used, with those specified in the corresponding section of the Underwriters' rules.

If the device only partly satisfies these rules, state which rule is not complied with, and suggest the changes necessary to make it "approved." Suppose, for instance, that you have to decide about a switch: you will find in the Code rule 51 relating to switches. Sections *a* and *b* of this rule refer to *all* types of switches, and it must first be decided, whether the particular switch satisfies the conditions specified there. Then, if it is a knife-switch, further requirements will be found under the sections *c* to *k*; if it is a snap switch, the rules *l* to *t* apply to it. For knife-switches you will find, that they must be mounted on non-combustible bases, that the hinges must be provided with spring washers in order to insure good contact, that the separation between the parts of opposite polarity must be not less than a certain limit, etc. See if all these requirements are fulfilled in the switch under inspection, and if not, state whether in your opinion the switch should be absolutely condemned, or if it could be used after certain changes.

Report your conclusions, referring to the rules by number (for instance, 51*m*), and give free-hand sketches suggesting some changes in the devices inspected.

754. EXPERIMENT 37-B. — Inspection of Installations. — The work consists in inspecting some actual wiring and installed machinery, and in comparing the installation with the requirements of the National Electrical Code. The following classes apply here:

A. Stations and Dynamo Rooms.
B. Outside work.
C. Inside wiring.

In order to perform the work intelligently and with safety, the general layout of the plant must be known, at least in its general features, such as source of power, the places of the main connections and cut-outs, voltage of the supply, etc.

The rules covering installations are too numerous to be learned in a few laboratory exercises; moreover, they are not all of the same importance. It is desired that the student should first get experience in the most important requirements of the National Electrical Code, namely, those relating to:

Generators (Rule 1);
Switchboards (Rule 3);
Motors (Rule 8);
Transformers (Rules 11 and 13);
Outside wiring (Rules 12*a* to 12*h*);
Inside wiring (Rules 14 to 17; 21; 24 to 28);
Arc lamps (Rule 29).

During the inspection of wiring be sure not to come in contact with live high-tension wires; also do not use screwdrivers, wrenches, etc., which may cause a short-circuit. Above all, do not open or close any switches, without permission from the proper authorities.

As this work of inspection does not require the use of any apparatus or current, part of the inspection can be done outside of the regular laboratory time. It is most earnestly recommended, that the student spend as much time as possible in inspecting the available installations, with the National Electrical Code in hand. This will give him one of those most valuable experiences, which no books can supply, and which enables a man to distinguish good workmanship from a "cheap job."

Report. State what machines and wiring have been inspected, and which rules found to be complied with. Where you think the installation is not in accordance with the National Electrical Code, state so, referring to the rule number, and suggest the necessary changes.

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